ARL-STRUC-NOTE-490 AR-002-973

(12)

AD-A142 083

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

STRUCTURES NOTE 490

THE USE OF INTERFERENCE-FIT BOLTS OR BUSHES AND HOLE COLD EXPANSION FOR INCREASING THE FATIGUE LIFE OF THICK-SECTION ALUMINIUM ALLOY BOLTED JOINTS

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J. Y. MANN; A. S. MACHIN; W. F. LUPSON
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COPY No

84 06 14 007

AUGUST 1983

AR-002-973

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SUMMARY

The detection of fatigue cracks at bolt holes in the main spar of the Mirage III wing during full-scale fatigue tests led to a requirement for refurbishment procedures to extend the fatigue lives at a number of critical locations. One of these, which is covered by this investigation, was the spar lower front flange. Flight-by-flight fatigue tests have been carried out to determine the relative fatigue performance of aluminium alloy bolted joint specimens of 28 mm thickness incorporating close-fit bolts, interference-fit bolts (0·4%), hole cold-expansion (3%), interference-fit steel bushes (0·3%) and a combination of cold-expansion and interference-fit bushes.

Compared with joints assembled with close-fit bolts in reamed holes, the ratios of lives of specimens incorporating interference-fit bolts, interference-fit bushes and cold-expanded bolt holes were about 9:1, 5:1 and 3:1 respectively. Furthermore, specimens with holes cold-expanded followed by the installation of interference-fit bushes resulted in a greater fatigue life than with interference-fit bushes alone.

Fractographic measurements of crack development from the bores of holes in specimens incorporating close-fit bolts in non cold-expanded (reamed) and cold-expanded holes clearly indicated much slower fatigue crack propagation rates from the cold-expanded holes until the crack length was close to the nominal region of transition from the residual compressive to tensile stress zone around the cold-expanded holes.

Fatigue tests on cold-expanded hole specimens at different spectrum scaling factors indicated that, under the loading sequence used, each 10% increase in stress reduced the life to about half that at the lower stress level.

It was concluded that if the refurbishment requirement involved the enlargement of bolt holes to remove fatigue cracks and also the subsequent periodic non-destructive inspection of the holes in service (which would be difficult if interference-fit bolts were used), then the use of interference-fit bushes either alone or in combination with hole cold-expansion should enable a satisfactory extension in fatigue life to be achieved for the detail of interest in the structure.

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1. INTRODUCTION

Full-scale flight-by-flight fatigue tests on the structure of the Mirage III fighter aircraft have been carried out at the Aeronautical Research Laboratories (ARL) and the Eidgenössisches Flugzeugwerk (F + W) Switzerland. The Australian wing fatigue test was terminated by a catastrophic failure which originated at the bottom of a blind hole in the lower flange of the main spar, while in the Swiss test the final failure also originated at the lower surface of the main spar of the wing, but at a front flange bolt hole. The two failure locations are shown in Fig. 1, and are described in detail in References 1 and 2. In addition, fatigue cracks were identified at a number of other locations in the wing structure (Ref. 3).

Because of a requirement to extend the life-of-type of the Mirage III, several investigations were undertaken at ARL to explore methods for improving the fatigue lives of portions of the main wing spar where cracks had been detected either in the full-scale fatigue tests or in service. Some of the results of these investigations—dealing with the inboard section of the rear lower flange of the spar—have already been published (Refs 4, 5, 6).

The present investigation relates to the lower front flange of the spar at a position corresponding to the failure location in the spar during the Swiss test (Fig. 1). Unlike the rear flange (where clearance-fit fasteners are installed) the front flange incorporates a series of 5 mm diameter interference-fit fasteners to secure the wing skin to the spar. Although interference-fit fasteners can provide significant improvements in fatigue life (Refs 7, 8), the maintenance of accurate hole sizing and bolt dimensions are essential if the full benefits are to be realised. With the small diameter (5 mm) bolts and relatively long holes (30 mm) in the Mirage front flange, some difficulties could have been expected in consistently obtaining the specified interferences (0·4 to 0·8%).

As a result of the information derived from tests on specimens representing the inboard section of the rear flange (Refs 5, 6), the fatigue life improvement techniques selected for the present investigation were cold-expansion of the bolt holes, the use of interference-fit steel bushes in bolt holes, and a combination of the two.

2. TEST SPECIMENS AND FATIGUE LOADING CONDITIONS

The main spar of the Mirage III is a large forging in aluminium alloy to the French Specification A-U4SG (equivalent to the American alloy 2014 which is covered by Specification QQ-A-255a). As inadequate quantities of A-U4SG were available at the time, the test specimens used in this investigation were made from an equivalent British alloy (B.S. L168) supplied in the form of 63·5 mm × 31·75 mm extruded bars. Specification values covering the tensile properties and chemical composition for the two alloys together with those derived from tests on the particular batch of material used (laboratory code GR) are given in Table 1.

Figure 2 illustrates the general type of low-shear-load-transfer bolted joint fatigue specimen used in this investigation. As shown it represents the detail at the 12th to 16th bolt holes along the front flange, the thickness of the test section (28 mm) corresponding to the nominal thickness of the flange at the 12th bolt hole. Tensile test specimens were taken from broken fatigue specimens. All fatigue and tension specimens had their longitudinal axes parallel to the direction of extrusion. Compact tension fracture toughness specimens (thickness 25 mm and 19 mm) were taken from offcuts of the extrusion at the positions shown in Fig. 3. The relevant test results are also given in Table 1.

The fatigue load spectrum (Fig. 4) adopted for this investigation was a simplified version (derived by Avions Marcel Dassault—AMD) of the Swiss Mirage full-scale wing test spectrum. It was transformed into a 100-flight load sequence, the breakdown of this sequence into four different flight types (A^1, A, B and C) being given in Fig. 5; and was identical to that used for

the previous fatigue tests (Refs 5, 6) on rear flange specimens. Cycles of +6·5 g/−1·5 g and +7·5 g/−2.5 g (a total of 39 cycles in 100 flights) were applied at a cyclic frequency of 1 Hz, whereas the remaining 1950 cycles per 100 flights were at 3 Hz. All fatigue tests were carried out in a Tinius–Olsen servo-controlled electro-hydraulic fatigue machine, the 100-flight load sequence being achieved using an EMR Model 1641 programmable function generator controlled by a punched tape and operating in sine wave mode.

Fatigue loads on most of the test specimens were derived on the basis that +7·5 g corresponded to a gross area stress* (not including the skin plates) of 235 MPa (34,100 psi), and that there was a linear stress/g relationship, i.e. the 1 g gross area stress was 31·3 MPa (4550 psi). Details relating to the derivation of these stresses are given in Appendix 2. In order to determine the effects on fatigue life of increasing and reducing the magnitudes of the stress levels in the sequence, specimens in one of the cold-expanded hole test series were tested with all stresses scaled by factors of 1·25 and 0·85 relative to the remainder of the series, i.e. at +7·5 g the corresponding stresses were 294 MPa (42,630 psi) and 200 MPa (28,900 psi) respectively.

3. FATIGUE TESTING PROGRAM AND RESULTS

The selection of potential life-enhancement systems for the front flange of the Mirage wing main spar was governed by the requirements that: (i) any existing fatigue cracks should be removed by reaming the holes and thus increasing their diameters and (ii) that refurbished holes should be readily inspectable in service (which would preclude the continued use of interference-fit bolts). Of the various refurbishment options available, cold-expansion of the bolt holes and the use of interference-fit steel bushes were considered to be the most promising. Both the hole cold-expansion and interference-fit bolt/bush systems for fatigue life enhancement depend on the introduction of residual stresses into the material surrounding the hole. Their application to aircraft structural joints has recently been reviewed by Mann and Jost (Ref. 10).

Several series of tests (totalling 39 specimens) were carried out using the following combinations of holes and fasteners. Details relating to specimen manufacture and assembly are given in Appendix 3.

(A) *5 mm straight-shank interference-fit bolts.* This series corresponded to the original structural detail and was used as a datum for comparing the effectiveness of the other test conditions. Bolt holes in the specimens were reamed to very close tolerances to accept bolts with nominally 0·4% to 0·8% interference. However, because of practical difficulties associated with bulging of the bolts which prevented those providing the higher interference from being fully inserted in the holes, the maximum value was maintained at about 0·4% by careful hole sizing and selection of bolts of the appropriate diameter. The individual bolt insertion forces are given in Appendix 3.† For these specimens (excluding GR1D‡) the average bolt insertion force was 10720 N (2410 pounds) and standard deviation 3520 N (792 pounds). For degrees of interference up to the maximum interference used in this investigation (0·4% in the case of interference-fit bolts) the maximum hoop stresses introduced into the aluminium alloy adjacent to the holes should (theoretically) not have caused yielding of the material. Their magnitudes for the various interference-fit conditions are given in Table 2.

Fatigue test results for this series of 'control' specimens are given in Table 3(A). The significance (for all test series) of the life to failure being associated predominantly with flight 42 is that this flight contains the maximum load range (+7·5 g to −2·5 g) which occurs only once in each 100-flight sequence.

* The ratio of gross/nett areas at the bolt hole sections in the 'control' and refurbishment configurations are given in Appendix 1. For this material the modulus of elasticity was taken as 73100 MPa ($10 \cdot 6 \times 10^6$ psi).

† The bolt hole identification system, (1) to (5), adopted in this investigation is indicated on Fig. 2.

‡ GR1D was the first specimen with interference-fit bolts and it was intended that they should have 0·6% to 0·8% interference. The high bush insertion forces reflect the difficulty in bolt insertion which was eliminated by adopting an interference of 0·4%.

(B) *5 mm straight-shank close-fit bolts.* An examination of the 5 mm front flange bolts and bolt holes in spars from several crashed aircraft indicated that the degree of interference of some bolts might have been much less than the nominal minimum value of 0·4%. Since fatigue perforaance would be expected to decrease with reductions in the degree of interference, a series of tests was conducted to assess the behaviour of specimens incorporating close-fit bolts with a clearance of 0·016 to 0·034 mm. The results of tests involving 5 mm close-fit bolts in reamed holes are given in Table 3(B).

(C) *Cold-expanded holes.* Cold-expansion of bolt holes using the Boeing Split-Sleeve process (Ref. 11) was investigated during the two complementary investigations (Refs 5, 6) into extending the fatigue life of the Mirage spar. The process involves radial plastic expansion of a hole and results in the development of both radial and tangential (hoop) compressive stress fields in the material adjacent to the hole (Refs 12–18). The magnitude of the latter can equal the compressive yield strength of the material. Irrespective of the precise shape of the residual stress field and the magnitudes of the stresses there is, at some distance from the edge of the hole which depends upon the material and degree of cold-expansion, a transition from a compressive to a tensile stress field. Although under the action of external tensile loadings some relaxation in the magnitude of these residual stresses may occur, the compressive stresses effectively decrease the mean stress of the fatigue cycle near the hole and result in a retardation of the development of any cracks which may form at the surface of the hole (Refs 11, 15, 19, 20). As a consequence the fatigue life can be increased (Ref. 6).

In order to introduce an effective compressive stress field around the hole the Process Specification for the Split-sleeve System (Ref. 21) requires that the "edge margin" (the distance from the centre line of the hole to the edge of the plate divided by the hole diameter) should be not less than 2·0. For the basic specimen illustrated in Fig. 2 this ratio is exactly 2·0 and in the cold-expanded specimen (because of considerable oversizing of the holes) 1·57. In the present investigation the degree of cold-expansion was nominally 3%. A consequence of the process is that plastic deformation (or surface upsetting) around the mandrel entry and exit faces of the cold-expanded holes also occurs (Refs 11, 15). The extent of the deformed areas on the fatigue test specimens is apparent in Fig. 6, which shows a face after filing flat to allow good bearing surfaces for the skin and packing piece in the assembled specimens.

Results of the tests involving cold-expanded holes alone are given in Table 3(C) and Fig. 7.

(D) *Interference-fit steel bushed holes.* Interference-fit steel bushes were successfully used to provide significant life extensions for thick-section bolted-joint specimens of the types used in the two complementary investigations (Refs 5, 6). Although the interference-fit bushing of small diameter bolt holes is not a widely used practice in aircraft structures, lugs incorporating thin interference-fit bushes are relatively common and significant increases in fatigue performance have been associated with their use (Refs 22–27). Improvements in fatigue life associated with the use of interference-fit bushes have been attributed, firstly, to a reduction in the relative movement between the bush and the lug hole because of the radial pressure associated with the interference (and hence a reduction in fretting compared with that resulting from a close-fit pin or bolt in the lug); and secondly to the pre-stressing effect of the bush in the hole which, although increasing the mean tensile tangential stress at the boundary of the hole on the transverse diameter, can significantly reduce the local alternating stress range in the region of crack initiation under conditions of repeated external loading (Refs 28–30).

According to Gökgöl (Ref. 29) the optimum design for an interference-fit bush in a lug results in a bush thickness of 0·05 to 0·10 times the hole diameter; whereas Lambert and Brailey (Ref. 31) have stated that a bush must have a diameter ratio (external/internal) of greater than 1·33 to produce the same effective interference as a solid pin of the same external diameter. For the first application in the current investigation the requirement was to provide for the removal of cracks of at least 1 mm in depth and to re-use the standard 5 mm bolts. A bush of nominally 8·15 mm external diameter was selected,* i.e. wall thickness of 1·57 mm and diameter ratio of 1·63. Although data on the effects of interference-fit pins and bushes on the fatigue behaviour of aluminium alloy lugs indicate that the extent of the improvement increases

* This external diameter allowed for the removal of at least 0·5 mm depth of metal after the first crack inspection which indicated a "crack-free" condition.

with the degree of interference (Refs 22–27), some problems had been experienced in inserting bushes with 0·6% interference (Ref. 5). Thus, a nominal interference of 0·3% was adopted for these tests to ensure that, within the range of accepted manufacturing tolerances for holes and bushes, an effective degree of interference of 0·25% to 0·35% could be achieved consistently.

Details of the bushes used in this investigation are given in Fig. 8. The bush material was grade 304 austenitic stainless steel having a UTS of 1017 MPa and 0·1% proof stress of 786 MPa. Stainless steel was selected to provide greater potential for through-the-bush crack detection using a rotating probe eddy current system. A barium chromate paste was used as a lubricant and corrosion inhibitor during the insertion of all bushes but, before insertion, the bushes were passivated in a nitric acid solution and the corresponding holes in the specimens given an Alodine 1200 treatment applied by brushing. All bushes were pressed in from the Datum Face using a small static testing machine, the sequence of bush insertion being holes 1, 5, 2, 4, 3. Individual bush insertion forces are given in Appendix 3. For these 8·15 mm bushed specimens the average bush insertion force was 17840 N (4010 pounds) with standard deviation of 7400 N (1663 pounds). The test results for specimens of this series are given in Table 3(D).

(E) *Cold-expanded and interference-fit bushed holes.* Information derived from tests on large rear flange specimens reported in Reference 5 and also on other specimens at a later stage of the same testing program suggested that cold-expansion alone of the front-flange bolt holes might not provide sufficient life to meet the life-of-type requirements of the spar. As the front-flange holes in the spars in two fatigue test wings and a number of service wings had already been cold-expanded, a series of tests was undertaken to explore whether the fatigue life could be improved by fitting interference-fit bushes in cold-expanded holes. The combination of cold-expansion and interference-fits has been referred to by Leis and Ford (Ref. 32), and discussed in more detail by Gibson *et al.* (Ref. 33). They showed that the resultant hoop residual stress field could be derived by combining those associated with each of the separate processes, the nett result being, however, a decrease in the magnitude of compressive stresses close to the hole compared with those introduced by the cold-expansion system alone.

The five bolt holes in each of the specimens used in this test series were firstly cold-expanded in an identical manner to those referred to in para. 3(C) above. They were then reamed to 7 mm diameter and fitted with grade 304 stainless steel bushes at nominally 0·3% interference in a similar way to those specimens described in para. 3(D). To achieve the recommended minimum external/internal diameter ratio of 1·33 and allow standard 5 mm bolts to be re-used for the specimen assembly the bush thickness adopted was 1 mm. Appendix 3 gives the individual bush insertion forces. For the 7 mm bushes the average bush insertion force was 12160 N (2734 pounds) with standard deviation of 2320 N (523 pounds). Table 3(E) gives the fatigue results for specimens of this type.

4. FATIGUE FRACTURES

The fracture surfaces of all specimens broken in this investigation are shown diagrammatically in Fig. 9, and photographs of representative fractures are illustrated in Fig. 10. Although the fatigue crack development which led to the final fractures of individual specimens was usually associated with one hole only, the actual fracture path in about 75% of the 39 specimens tested in this investigation passed through an adjacent bolt hole. In at least ten specimens this fracture path revealed the development of fatigue cracking in an adjacent hole and, in such cases, the illustrations in Fig. 9 represent a composite section embracing the two holes. With the exceptions of specimens GR3B, GR15D and GR23E the crack development at the second hole within the fracture path was relatively minor. For GR15D the extent of fatigue cracking at holes 1 and 2 was such that either hole could be regarded as the "failure hole". Furthermore, for the unbushed specimens incorporating clearance-fit bolts, i.e. Types (B) and (C), there was usually evidence of quite extensive fatigue crack development in the equivalent hole at the other end of the test section to the final fracture hole.

Some of the general characteristics of the fatigue fracture development associated with the five types of specimens can be correlated by combining them into two Groups, i.e.

Group 1—those incorporating interference-fit bolts or bushes, i.e. Types (A), (D) and (E).

Group 2—those without interference-fit bolts or bushes, i.e. Types (B) and (C).

This leads to the following observations:

(i) Nine of the 13 specimens in Group 1 failed at bolt hole 1 or 5, whereas only one (GR20D)—or two if GR15D is included—of the 24 specimens in Group 2 failed at these holes. Most of the Group 2 specimens failed at holes 2 or 4.

(ii) With one exception (GR20E—Fig. 10(c)) the primary fatigue crack development in Group 1 specimens was associated with fretting at one or both of the faces of the specimens (Figs 10(a) and 10(b)) either from the pressure cone area under the washer at the nut face (Type (A)) or near the bush/hole edge interface (Types (D) and (E)). In the exception (GR20E) the primary fatigue cracking was from multiple-initiation along the bore of a bolt hole. Substantial secondary crack initiation down the bore was exhibited by specimen GR22E. This characteristic was also exhibited (but to a much lesser extent) by most other Group 1 specimens. Propagation from multiple fatigue crack initiation along the bore of a hole (Figs 10(d) to 10(f)) was, however, the predominant mode of crack development in specimens of Group 2; the exceptions being GR20D and GR15D both of which have been specifically referred to in (i) above.

(iii) Comparing specimens of Types (B) and (C). Multiple crack initiation along the bores of holes was common in all of these specimens. In those of Type (B)—clearance bolts in reamed holes—the primary fatigue crack initiation was at about the centre of the section (Fig. 10(d)). For those of Type (C)—clearance bolts in cold-expanded holes—the primary initiation was usually at between 2 mm and 4 mm from one of the faces (Fig. 10(e)).

5. FATIGUE CRACK PROPAGATION RATES

Because the variety of primary fatigue crack initiation sites (both at the bores of the holes and at the faces of the specimens) and the marked differences in the shapes of the fatigue crack fronts as they developed, it was decided to limit the analysis of crack propagation to specimens in which the cracks had initiated at the bore of the holes and had led to the development of similar crack profiles. With these restrictions, only selected specimens of the "5 mm clearance-fit bolts" and "cold-expanded holes" were considered suitable for determining fatigue crack propagation rates using fractographic examination. Holes fitted with interference-fit bolts and bushes did not satisfy these criteria. The following specimens were selected:

(a) clearance-fit bolts—GR7B, failure hole 4 (Fig. 10(d))
—GR5B, failure hole 4 (Fig. 11(a))
—GR3B, "non-failure" hole 2* (Fig. 11(d))

(b) cold-expanded —GR9D, failure hole 4 (Fig. 11(b))
—GR2D, failure hole 2 (Fig. 11(c))
—GR9D, "non-failure" hole 2.

Using the feature on the fracture surfaces resulting from the application of the $-2{\cdot}5$ g to $+7{\cdot}5$ g load as a marker, the incremental crack growth was measured (using an optical microscope) backwards from the last application of this load until a crack length at which the markings became unrecognizable. For specimens GR7B, GR5B, GR9D (hole 4) and GR2D this point was reached at a distance from the hole (crack origin) of between about 0·3 and 0·6 mm. For these specimens crack growth from both sides of the particular failure holes was measured. As the area close to the initiation of the crack at hole 2 in specimen GR3B showed less evidence of damage during crack development it was possible, in this case, to measure crack increments

* A hole at which a fatigue crack had initiated, but was not in the path of the final fracture.

at only 0·02 mm from the hole. The fracture surface adjacent to this particular hole is illustrated in Fig. 11(d) where the multiple crack origins are clearly shown. Crack growth measurements were made at both origins 'A' and 'B'. Although the measurements from both origins were in good agreement, those reported here were from origin 'A' because it was possible to measure to shorter crack lengths in this case. Multiple crack origins for the cold-expanded hole specimen GR9D (hole 2) were also evident. It was hoped to obtain similar measurements at short crack lengths from this hole, but although very clear fractographic markings were evident at crack lengths exceeding about 0·7 mm they suddenly became indistinct and their continuity could not be identified at shorter crack lengths.

The fatigue crack propagation curves for cracks initiating at the five holes studied in this investigation—three clearance-fit bolt and two-cold expanded holes—are shown in Fig. 12.

6. STATIC FAILING LOADS OF SPECIMENS

The load levels at which individual specimens actually failed by complete fracture were determined from the continuous analogue records used to monitor each specimen. They are given in Table 3. With only one exception (Specimen GR9D-Type(C)) specimens tested under the conditions in which +7·5 g corresponded to 235 MPa all failed at loads just less than that for the +6·5 g level or between the +6·5 g level (274 kN) and +7·5 g level (316 kN). In general, when failure occurred in flight 42 (i.e. the Type A^1 flight which included the only application of the +7·5 g level in the 100 flight sequence), the failing load exceeded 274 kN; and when it was less than 274 kN the flight at failure corresponded to one of the 18 occurrences of the Type A flight per 100 flights, in which the maximum level is +6·5 g.

The multiplicity of fatigue crack origins, complicated crack geometries and depths of cracks relative to the distance from the bolt holes to the sides of the specimens were not conducive to making meaningful estimates of failing loads using methods of analytical fracture mechanics, as typified by those of Newman and Raju (Ref. 35).

7. DISCUSSION

Table 4 summarises the results of the fatigue tests and provides a comparison of the average lives for the five hole treatments covered in this investigation. The results of Swiss (Ref. 7) and French (Ref. 8) fatigue investigations on specimens of essentially the same aluminium alloy incorporating interference-fit bolts, clearance-fit bolts and cold-expanded holes and tested under similar flight-by-flight loading sequences are summarised in Table 5.

These Tables show the superiority of the interference-fit bolt fastening system relative to the other four types of systems investigated as refurbishment options for the particular part of the Mirage IIIO spar under consideration. They indicate, in particular, the significant reductions in fatigue lives resulting from the use of clearance rather than interference-fit bolts (a life ratio of 0·11 in the current investigation and 0·12 in the Swiss tests), and the poor performance of cold-expanded hole specimens compared with those having interference-fit bolts; life ratios of 0·30, 0·42 and 0·52 in the current, French and Swiss tests respectively. The last results confirm the findings of Moore (Ref. 36) that interference is about twice as effective as hole cold-expansion in fatigue life enhancement. Nevertheless, cold-expanding alone, the installation of interference-fit bushes and a combination of the two provide increased lives compared to the use of clearance-fit bolts.

Because of the nominally higher interference-fit stresses induced by the bolts compared with the bushes (see Table 2) it was not unexpected that specimens incorporating interference fit-bolts demonstrated significantly longer lives than those with interference-fit bushes alone. However, as indicated in Appendix 1, the cold-expanding and bushing systems all involved increases in the nett area stresses compared with those employing 5 mm bolts in 5 mm holes. Reference to Figure 7 indicates that under the particular loading spectrum and sequence used, each 10% increase in stress reduces the total life to about half that at the lower stress level. If, in the case of the cold-expanded and bushed specimens, the comparison with the interference-fit bolt specimens is made on the basis of nett area stresses, the equivalent fatigue life (derived using the equation for the curve in Fig. 7) is 82,035 flights. This is not significantly different from the 72,524

flights of the interference-fit bolt specimens. Thus, providing the nett areas were the same, the combination of cold-expanding and bushing—which would provide the option for an easily demountable fastener—could provide a similar fatigue performance to that resulting from the initial selection of interference-fit bolts. Furthermore, in the present refurbishment situation, the bushing of a cold-expanded bolt hole has the potential for providing a significant increase in life compared with that obtainable by cold-expansion alone, in the event that the life achieved by cold-expansion alone is not adequate.

When assessing the relative fatigue performances of the various systems employed in the current investigation it should be noted that for specimens incorporating clearance-fit fasteners the fatigue failures usually developed from multiple crack initiation within the bore of the holes, whereas those incorporating interference-fit bolts or bushes failed from fretting-initiated cracks on one or both of the faces of the specimens a little distance from the hole edge. Presumably, if surface-fretting crack initiation had been suppressed, any "hole-bore" cracks which had initiated in the interference-fit specimens would have resulted in greater lives than actually occurred, and thus the lives for most of the specimens in Tables 3(A), 3(D) and 3(E) represent the lower limits of those which might be associated with these particular fastener systems under the current test conditions.

Figure 12 illustrates the beneficial effects on total life by cold-expanding compared with the simple reaming of bolt holes over the range of crack length measurements. It also shows (except in the final stage of crack development when the crack lengths are relatively long) that the propagation rates of fatigue cracks emanating from cold-expanded holes are considerably less than for cracks from non cold-expanded holes. Although the fatigue crack development shown in Fig. 12 represents a situation of crack initiation within the bores of 28 mm long holes well away from the faces of the specimens, the shapes of the fractographically-determined crack propagation curves for both "as-reamed" and "cold-expanded" hole specimens are quite similar to those reported by Chandawanich and Sharpe (Ref. 37) for surface crack measurements from open holes in 7075-T6 aluminium alloy sheet. Clearly, cold-expansion of the holes has not prevented crack initiation at the holes in either the current tests or those reported in Reference 37. However, because of the differences in specimen design, i.e. filled and open holes, the complications of bolt bearing at the hole surface and fretting would have been absent in the tests of Chandawanich and Sharpe. It is thus of interest that the crack propagation behaviour found in the current tests and those of Chandawanich and Sharpe appear to be similar, irrespective of the likely differences in fatigue crack initiation in the two types of specimens used.

In contrast to the present investigation, Chandawanich and Sharpe were able to measure crack growth for cracks as small as 0·1 mm in length, and their data for cold-expanded hole specimens suggests a relatively rapid rate of crack propagation from initiation to a length of about 0·5 mm. Similar behaviour has been reported by Noronha *et al.* (Ref. 38) who have inferred that for short cracks (less than 0·7 mm length in their specimens) the fatigue crack propagation rate from cold-expanded holes is greater than from conventionally drilled holes. In reviewing the crack growth behaviour of short cracks initiating at notched specimens, El Haddad *et al.* (Refs 40, 41) have shown that such cracks can have considerably higher crack propagation rates than would be predicted by stress-intensity crack growth laws for large cracks. Under remote tension loading the initial rapid propagation rates decrease as the crack grows through the diminishing stress or strain concentration field of the notch. After reaching a minimum value the crack propagation rate increases as it grows past the zone of influence of the notch, and its growth characteristics then become describable by the fracture mechanics solutions for long cracks. Although this argument could be extended to the case of short cracks from cold-expanded holes, the situation is complicated by the interaction of the locally high tensile stress field resulting from the stress concentrating effect of the hole and that associated with hole cold-expansion—both before and after fatigue crack initiation. Furthermore it is likely that, under fatigue cycling, some gradual relaxation of the residual stresses would occur (Ref. 42).

Examples of the residual stress distributions surrounding cold-expanded holes in aluminium alloy sheet/plate given by Chang (Ref. 13), Gibson *et al.* (Ref. 33) and Chandawanich and Sharpe (Ref. 37) suggest that, in an uncracked specimen, the transition from a compressive to a tensile residual stress field occurs between about two-thirds and one hole radius from the edge of the hole. Although the residual stress distribution will change as the fatigue crack propagates, it is of interest that in both the current tests and those reported in Reference 37 the transition

from an almost constant crack propagation rate (the intermediate stage occupying some 70% of the crack propagation life) to the much more rapid crack growth prior to final failure occurs at a crack length corresponding to about this same distance from the edge of the hole. Chandawanich and Sharpe have also demonstrated the significance of crack closure effects within the compressive stress zone during the intermediate stage of crack propagation from cold-expanded holes. Nevertheless, the fact that fatigue cracks propagated through the zone of compressive residual stress (although at a reduced rate compared with those from non cold-expanded holes) indicates that the effective stress intensity at the crack tip exceeded the threshold stress intensity range for crack propagation. Otherwise, the crack would have been contained within the compressive stress zone and met the criterion enunciated by Grandt and Gallagher (Ref. 43) for the design of "long-life" fastener systems.

A concern which has been expressed on several occasions (Refs 44–46) is that, although fatigue life enhancement systems can provide an acceptable increase in average lives, they may result in increased scatter in life. Thus, at the usually acceptable probabilities of failure, little might be gained from the fatigue viewpoint in adopting some systems. It is therefore of interest to note that in the current tests the scatter in life (defined as the standard deviation of log. life) for the 5 mm clearance-fit bolt condition (which resulted in the worst fatigue performance) and that for each of the four life-enhancement systems investigated is not significantly different.

It cannot be overemphasised that the effectiveness of interference-fit bolt and bush faste systems for providing consistent increases in fatigue lives relies critically on the achieven of the correct degree of bolt or bush to hole interference along the entire length of the hole around the whole periphery. This, in turn, requires the maintenance of close dimensi tolerances during the manufacture of the bolt/bush and machining of the hole, and very ca control during the insertion of the bolts or bushes. If these can be achieved, the use of interfere fit bolts or bushes can provide a much more effective fastener system than that embodying h cold-expansion alone. Nevertheless, an important consideration in the selection of a life-enhancement fastener system could be the philosophy of in-service monitoring of the joint in question. If non-destructive inspections of the holes were required to provide added assurance of the absence of crack development, or a requirement existed for disassembly of the joint, these actions could be more readily achieved in situations where the fasteners were easily removable. Under these circumstances a simple hole cold-expansion system could, despite its relatively worse fatigue performance, be an acceptable alternative to the use of interference-fit bolts or bushes. It also has the advantage of allowing the use of wider dimensional tolerances than in the interference-fit cases.

8. CONCLUSIONS

1. This investigation has demonstrated the effectiveness of interference-fit bolts or bushes and hole cold-expansion for improving the fatigue lives of thick-section aluminium alloy bolted joints. Compared with joints fitted with close-fit bolts in reamed holes, the ratio of the lives of specimens incorporating interference-fit bolts, interference-fit steel bushes and cold-expansion of bolt holes were approximately 9:1, 5:1 and 3:1 respectively.

2. Hole cold-expansion followed by the installation of interference-fit bushes resulted in a further increase in fatigue life compared with that resulting from interference-fit bushes alone.

3. Fatigue crack propagation from the bores of cold-expanded holes is much slower than that from non cold-expanded (reamed) holes until the crack length is close to the region of transition from the residual compressive to tensile stress zone around the cold-expanded hole.

4. Under the particular loading spectrum and sequence used in this investigation, each 10% increase in stress reduces the total life to about half that at the lower stress level.

5. If the refurbishment of the front flange of the Mirage III main spar requires that the bolt holes be enlarged to remove fatigue cracks and the holes to be periodically inspected in service, then the incorporation of interference-fit bushes either alone or in combination with cold-expansion of the holes should enable a satisfactory extension in fatigue life to be achieved in service for this detail of interest in the structure.

6. The effectiveness of interference-fit bolt and bush fastener systems for providing consistent increases in fatigue lives relies critically on the achievement of the correct interferences which, in turn, require the maintenance of close dimensional tolerances for bolts, bushes and holes, and careful control during the insertion of bolts or bushes.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the staff of Structures Division who determined the mechanical properties of the test material, to Mr L. Wilson of Materials Division for carrying out the chemical analysis, and to Corporals A. Green and S. Nicoll of the RAAF for assistance in the preparation of test specimens and photography of the fracture surfaces.

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APPENDIX 1

Ratios $\frac{\text{gross area}}{\text{nett area}}$

Specimen type	Hole diameter, nominal (mm)	$\frac{\text{gross area}}{\text{nett area}}$
Interference-fit bolts	4·96	1·12
Clearance-fit bolts	5·02	1·12
Cold-expanded holes	6·36	1·15
Interference-fit bushes	8·15	1·20
Cold-expanded holes and interference-fit bushes	7·02	1·17

(Gross area = 1344 mm²).

APPENDIX 2

Derivation of test stresses

The stress at 7·5 g was derived from strains measured at gauge 1·4T during the 1979 strain survey of the left-hand Swiss Mirage test wing. This gauge was located at the inner surface of the lower front flange of the main spar between bolt hole no. 14 and the spar web, and a multiplying factor of 1·2 was used to estimate the strain at the Swiss failure location (hole no. 12). Two different methods were used to estimate the strain at 7·5 g, and the value of 235 MPa (34,100 psi) adopted for this investigation was an average of the two. The first was determined directly from the actual numerical value of strain at 5 g using the ratio 7·5 (g)/5 (g) and resulted in a strain of 3240 microstrain (stress 237 MPa; 34,340 psi). The second method was based on the average microstrain per g from the 1 g to 5 g increment (Ref. 9) and resulted in a strain of 3201 microstrain (stress 234 MPa; 33,930 psi).

APPENDIX 3

Specimen manufacture and assembly

(*a*) *Interference-fit bolt and bush insertion forces—maximum* (N)
(bushes inserted from datum face)

Specimen group	Spec. No. GR	Hole No. 1	2	3	4	5
Interference-fit bolts (5 mm)	1D	31140	29800	22240	22240	26690
	5A	8900	15120	8900	9790	7120
	7A	16460	9340	15570	6230	9790
	16A	11120	11120	17790	8010	11120
	22A	14680	11790	5780	8670	7120
Interference-fit bushes (8·15 mm)	17E	24470	6670	6670	10680	17790
	20E	25800	4890	13340	12010	21350
	23E	19130	22240	21350	23580	22690
	12E	13340	10680	13340	11790	26690
	25E	35590	20020	20910	16460	24470
Interference-fit bushes (7 mm)	7D	8010	11120	9120	11120	9560
	22D	11120	9120	11570	12010	13570
	11D	12010	15790	10680	10680	12900
	21D	11570	17790	15570	11120	11120
	17D	14680	12010	14230	12900	14680

Sequence of bolt or bush insertion: 1, 5, 2, 4, 3.
Lubricant/Inhibitor: bolts—light oil, Bolicone grease 73
bushes—barium chromate.
Nominal interference: bolts 0·4%; bushes 0·3%.
Bushes: Passivated in a nitric acid solution.
Bushed holes in specimens: Brush alodine 1200 treatment.

(*b*) *Boeing split-sleeve cold-expansion*
Starting hole size: 6·058 to 6·063 mm dia.
Finished hole size (after reaming): 6·350 to 6·368 mm dia.
Degree of cold expansion: 3 to 3·1%. [Elastic recovery of the test specimen material occurs after withdrawal from the hole of the cold-expansion tool. The degree of cold-expansion is defined as the percentage difference in diameter between the starting hole size, and the maximum mandrel diameter plus twice the sleeve thickness].
Type of bolts: (non bushed holes). 0·250 inch dia. AN4-15—cadmium plated.
Orientation of split in sleeve: Split facing datum end.
Sequence of hole expansion: 1, 2, 3, 4, 5.

(*c*) *Bolts*
Sequence of tightening: 2, 5, 1, 4, 3.
Torque: (5 mm) 3·95 Nm, 35 in. lb.; (0·250 inch) 7·9 Nm, 70 in. lb.

TABLE 1

Properties of test material

(a) Chemical composition (%)

Element	‡Specification A7-U4SG (2214)	British Standard L168: 1978	Test material GR
Cu	3·9–5·0	3·9–5·0	4·29
Mg	0·2–0·8	0·2–0·8	0·43
Mn	0·4–1·2	0·4–1·2	0·76
Fe	0·30 max.	0·50 max.	0·23
Si	0·5–1·2	0·5–0·9	0·74
Ti	0·15 max.	0·15 max.	not analyzed
Cr	0·10 max.	0·10 max.	0·01
Zn	0·25 max.	0·25 max.	<0·20

(b) Static tensile

Property	‡Specification A7-U4SG (2214)	British Standard L168: 1978	Test material GR
0·1% proof stress (MPa)	—	—	466 (sd 10)
0·2% proof stress (MPa)	390	440	474 (sd 12)
Ultimate tensile stress (MPa)	450	490	524 (sd 12)
Elongation (%)	5	7	11 (sd 2)
0·1% PS/Ult	—	—	0·89

sd = standard deviation.

(c) Fracture toughness (K_{Ic})

Specimen thickness (mm)	MPa.m$^{1/2}$	ksi.in$^{1/2}$
25	34·5*	31·5*
19	32·0†	29·2†

* Average of two specimens from the one bar.

† Average of five specimens from different bars.

‡ *Conditions de controle des produits lamines en alliages d'aluminium utilises dans les constructions aerospatiales.* Ministere de la Defense, Direction Technique des Construction Aeronautiques AIR 9048, Edition No. 1, 26 December, 1978, p. 91. [Specification A7-U4SG superseded A-U4SG, the material from which the spars were manufactured].

TABLE 2

Residual tensile hoop stresses at holes induced by interference-fit bolts and bushes (Ref. 34)

Condition	Interference (%)	Maximum hoop stress (MPa)
5 mm interference-fit steel bolt	0·4	193
8·15 mm external diameter steel bush (5 mm internal)	0·25 0·35	117 163
7 mm external diameter steel bush (5 mm internal)	0·25 0·35	95 133

TABLE 3

Fatigue test results

Specimen No. GR	Gross area stress (MPa) at +7·5 g*	Life (flights)	Failure hole No.	Failing load (kN)
(A) *5 mm Interference-fit bolts (0·4%–0·8%)*				
16A	235	52,742	1	276
5A	235	59,618	5	268
22A	235	79,700 [81,500]†	Test terminated. Specimen not disassembled. Further testing indicated that crack of 11 mm×9 mm at hole 1 had developed by 79,700 flights (see Fig. 9A)	
7A	235	92,700	Test terminated. Specimen disassembled. No crack indications	
	‡Log. average = 72,524; s.d. = 0·113			
1D	210	80,200	Test terminated. Specimen disassembled. No crack indications	
(B) *5 mm Clearance-fit bolts*				
6B	235	5,642	4	288
3B	235	7,399	4	266
7B	235	8,099	4	264
2B	235	8,742	2	293
5B	235	9,127	4	267
	Log. average = 7,695; s.d. = 0·083			
1B	210	12,942	2	281
(C) *Cold-expanded holes—Boeing process 2·5–3·4% expansion (0·25 inch AN4 bolts—6·35 mm)*				
16D	294	2,362	2	336
26D	294	2,818	4	340
5D	294	2,913	4	338
8B	294	3,136	4	330
12B	294	3,223	4	332
	Log. average = 2,874; s.d. = 0·053			
6D	235	14,742	4	303
19D	235	16,542	4	264
3D	235	20,427	4	265
23D	235	24,413	4	271
9D	235	25,813	4	240
11B	235	25,842	2	283
2D	235	26,781	2	267
	Log. average = 21,570; s.d. = 0·104			

TABLE 3 (Continued)

Specimen No. GR	Gross area stress (MPa) at $+7 \cdot 5\ g$*	Life (flights)	Failure hole No.	Failing load (kN)
1E	203	24,300	Test terminated. Residual static load 523 kN through crack at hole 4	
10B	200	49,242	4	265
15D	200	51,987	1/2	230
18D	200	55,336	2	232
20D	200	64,142	5	257
4A	200	78,041	4	230
	Log. average = 58,904; s.d. = 0·081			
(D) *Stainless steel interference-fit bush 8·15 mm dia., (5 mm bolts)*				
17E	235	27,013	2	271
20E	235	30,227	2	274
23E	235	41,242	1	292
12E	235	41,542	1	282
25E	235	61,342	2	287
	Log. average = 38,610; s.d. = 0·139			
(E) *Cold-expanded holes—Boeing process as* (C); *then reamed to 7 mm dia. and stainless steel interference-fit bushed, (5 mm bolts)*				
21D	235	48,042	5	Not recorded
7D	235	54,042	1	302
22D	235	55,542	2	278
11D	235	63,142	1	310
17D	235	65,899	1	267
	Log. average = 56,969; s.d. = 0·055			

* Nominal machine forces at '$+7 \cdot 5\ g$' load.

$7 \cdot 5\ g$ stress (MPa)	force (kN)
200	269
203	274
210	284
235	316
294	395

† By comparing crack sizes and crack propagation rates in specimens GR16A, GR5A and GR22A it was estimated that the complete failure of specimen GR22A would have occurred in a further 1400 to 2100 flights. For analytical purposes the life to failure has been estimated as 81,500 flights.

‡ Estimated using method in Reference 39 for truncated samples.

TABLE 4

Summary of fatigue test results

(for 7·5 g stress = 235 MPa)

Specimen type		Log. average life (flights)	Life ratios
(A)	5 mm Interference-fit bolts	72,524	
(B)	5 mm Clearance-fit bolts	7,695	(B)/(A) = 0·11
(C)	Cold-expanded holes (6·35 mm)	21,570	(C)/(A) = 0·30 (C)/(B) = 2·80
(D)	Interference-fit bushes (8·15 mm)	38,610	(D)/(A) = 0·53 (D)/(B) = 5·02 (D)/(C) = 1·79
(E)	Cold-expanded holes and interference-fit bushes (7 mm)	56,969	(E)/(A) = 0·79 (E)/(B) = 7·40 (E)/(C) = 2·64 (E)/(D) = 1·48

TABLE 5

Summary of French and Swiss tests with interference-fit bolt, clearance-fit bolt and cold-expanded hole specimens (Refs 7 and 8)

Specimen type		Log. average life (flights)	Life ratios
(A_F)	5 mm Interference-fit bolts	67,105	
(C_F)	Cold-expanded holes (5 mm)	27,987	(C_F)/(A_F) = 0·42
(A_S)	6·3 mm Interference-fit bolts	78,646	
(B_S)	6·3 mm Clearance-fit bolts	9,403	(B_S)/(A_S) = 0·12
(C_S)	Cold-expanded holes (6·3 mm) Edge margin = 2	40,553	(C_S)/(A_S) = 0·52 (C_S)/(B_S) = 4·31

For French (F) 7·5 g stress = 210 MPa (30,500 psi).

For Swiss (S) 7·5 g stress = 266 MPa (38,600 psi).

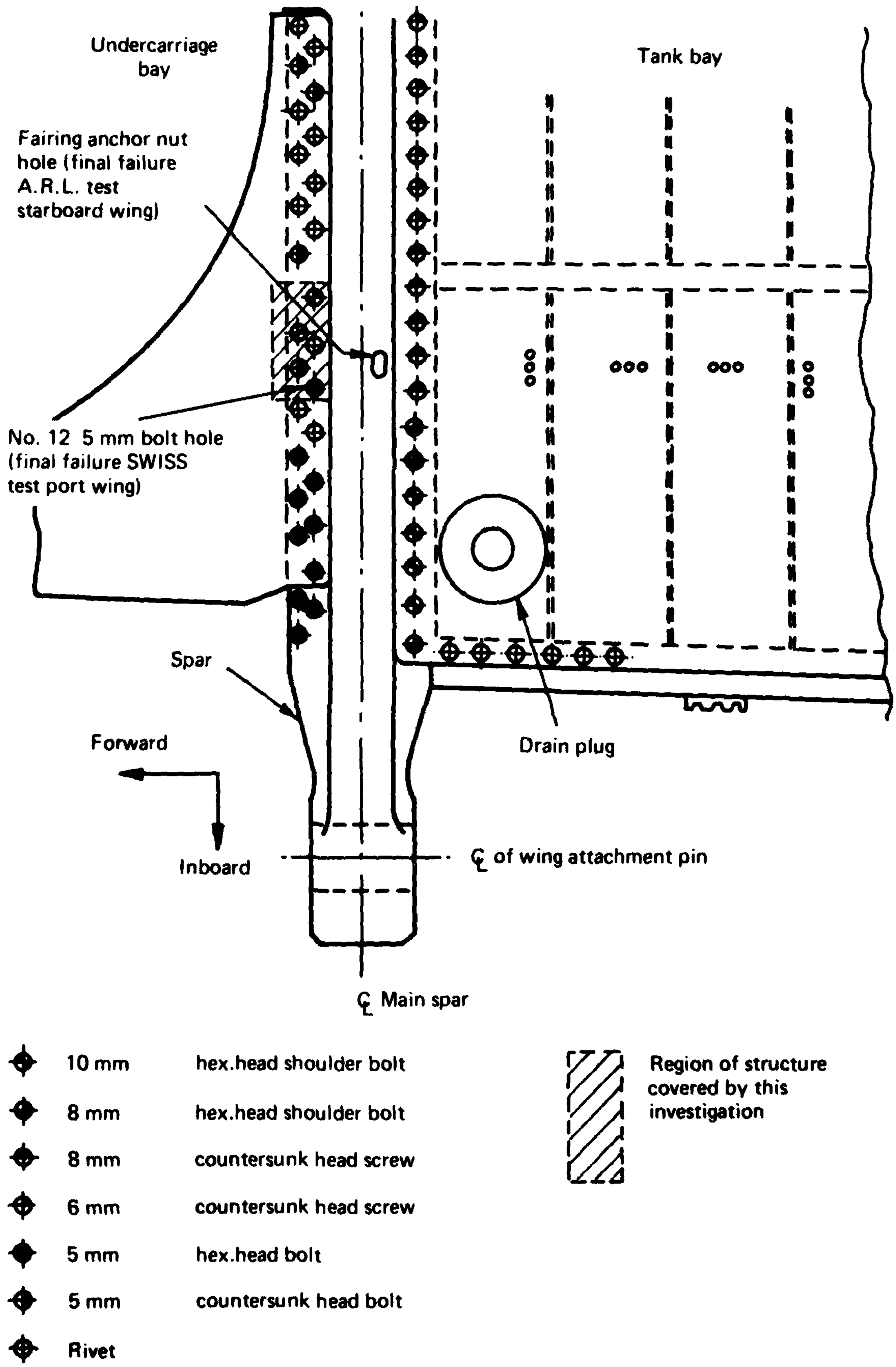
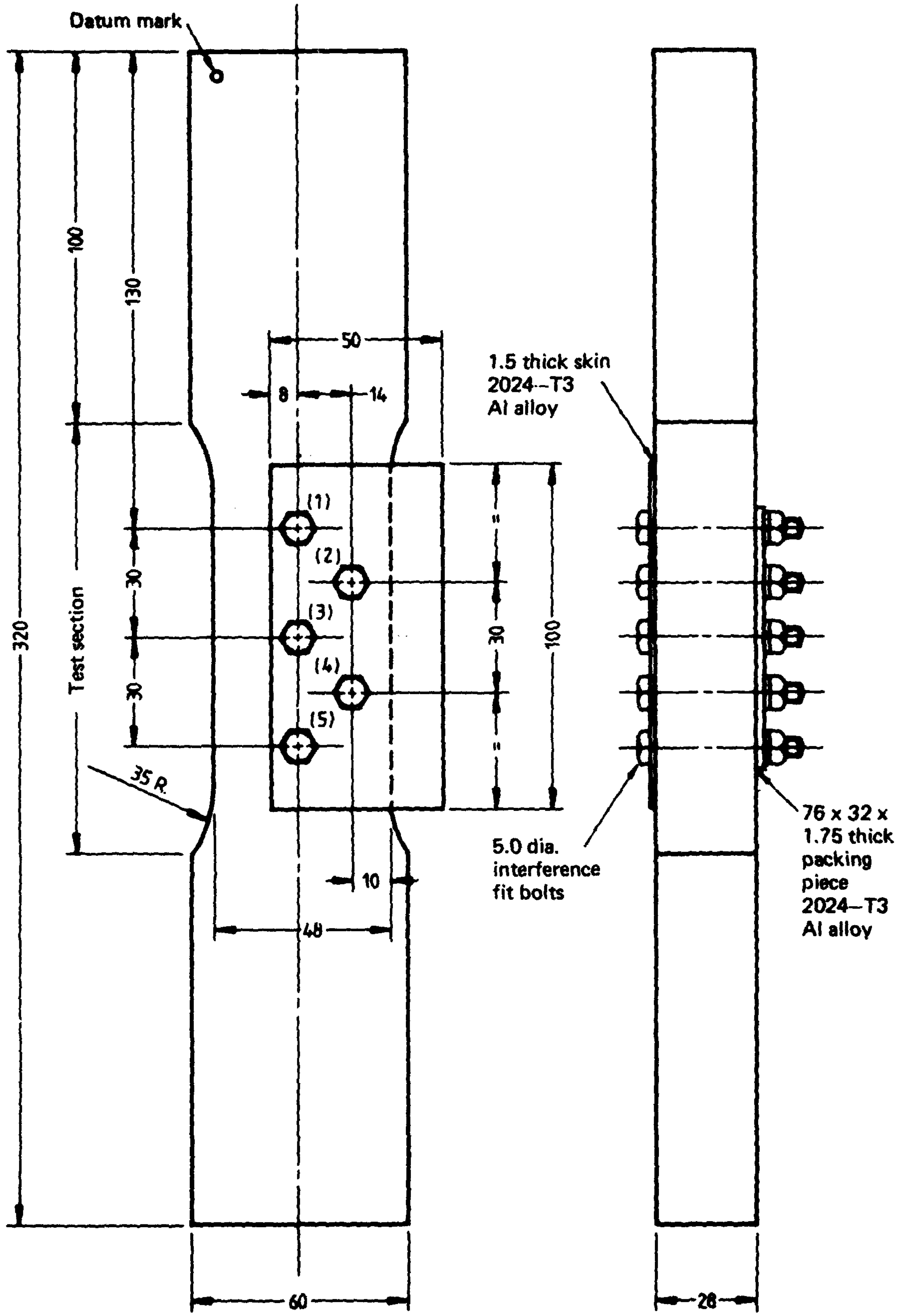


FIG. 1 MIRAGE PORT WING VIEWED FROM LOWER SURFACE



All dimensions in mm
Bolt hole positions in specimen
indicated by number in (   )

Material: BS.L168 Al alloy

FIG. 2 MIRAGE SPAR LOWER FRONT FLANGE FATIGUE SPECIMEN

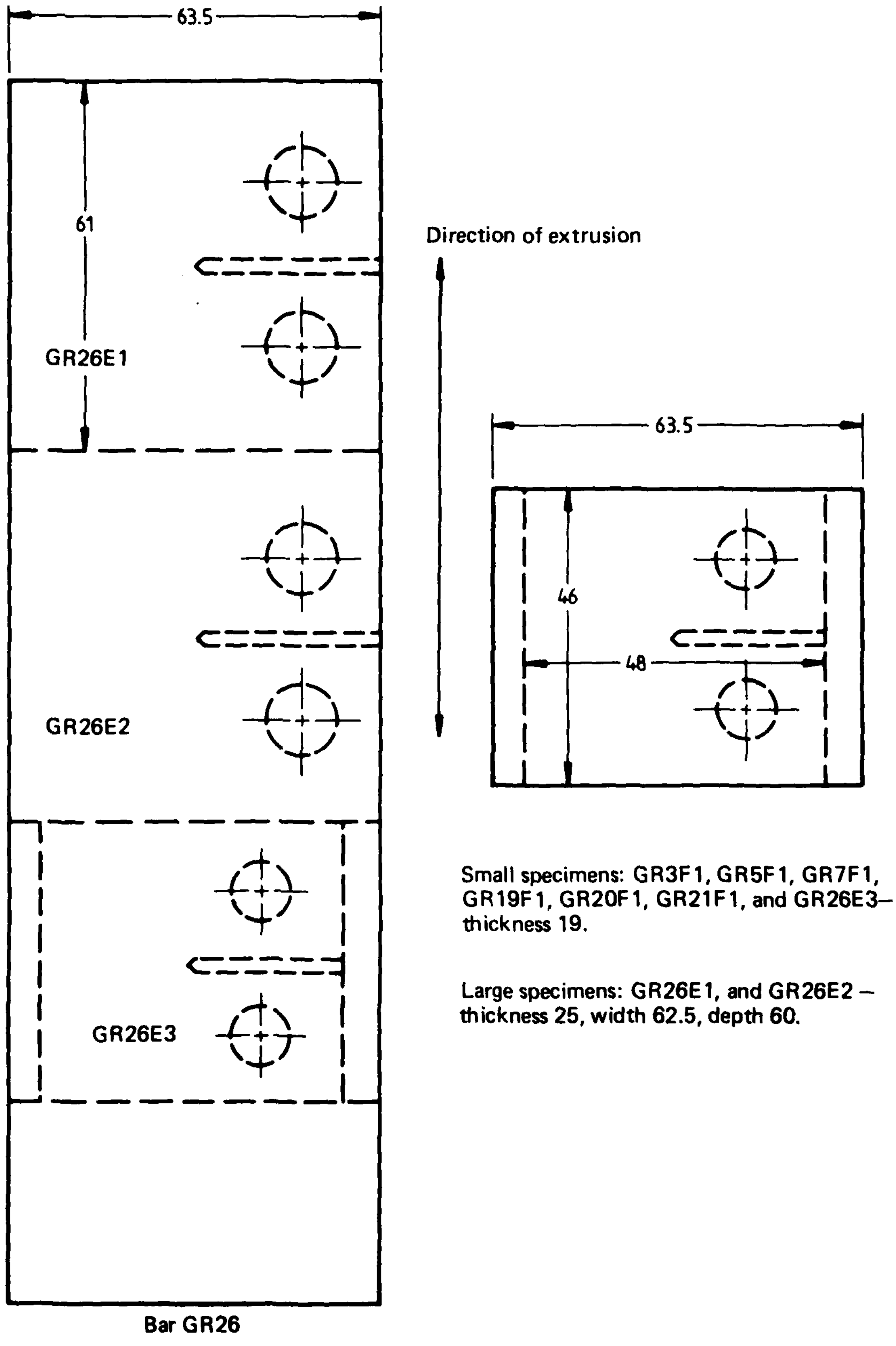


FIG. 3 LOCATIONS OF COMPACT TENSION FRACTURE TOUGHNESS SPECIMENS IN EXTRUDED BARS.

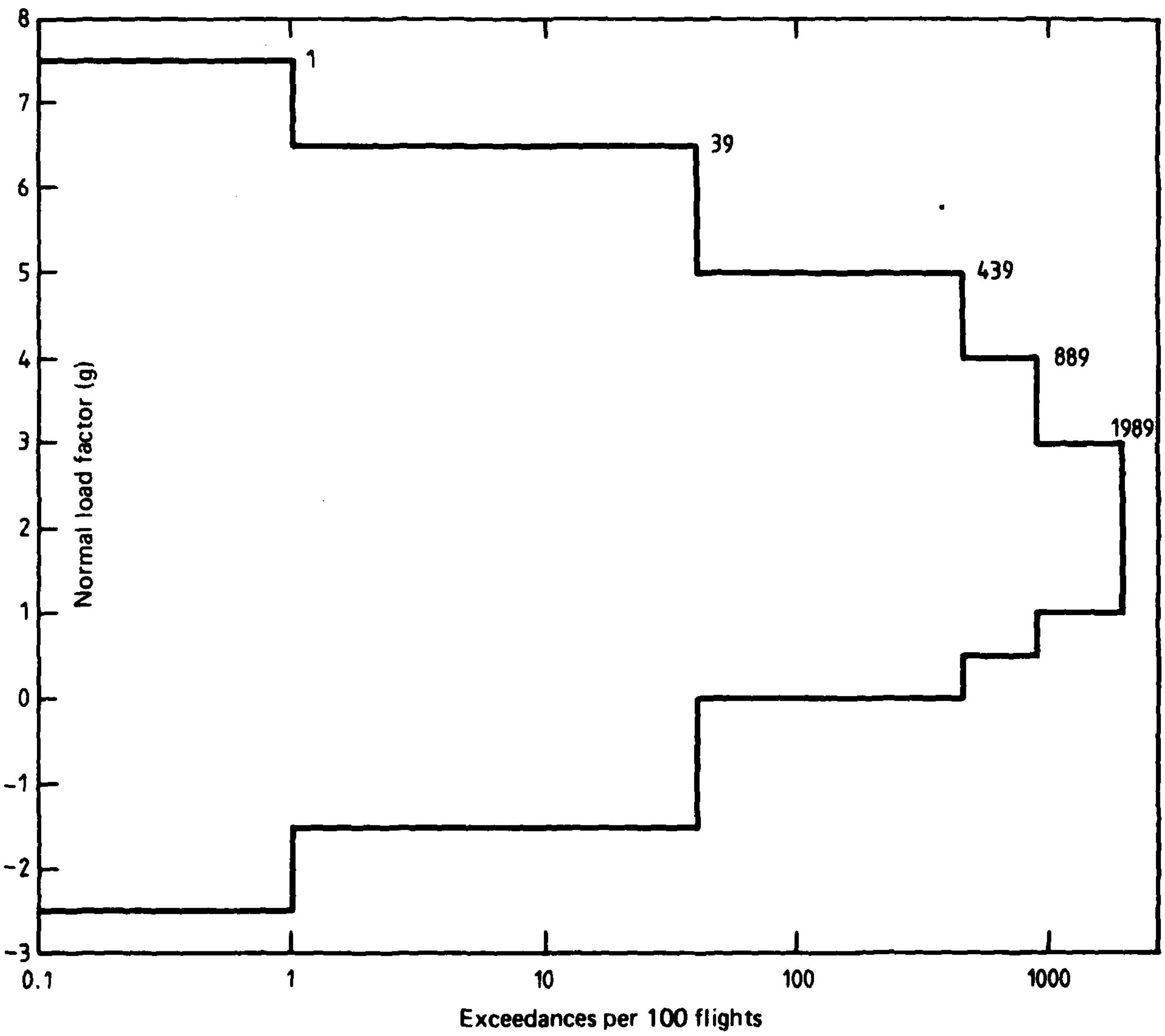


FIG. 4 TEST LOADING SPECTRUM FOR 100 FLIGHTS

100 FLIGHTS (1989 CYCLES) REPRESENT 66.6 HOURS OF FLYING

FLIGHT A' →	10 CYCLES +3g/+1g	5 CYCLES +4g/+0.5g	2 CYCLES +5g/0g	1 CYCLE +6.5g/-1.5g	1 CYCLE +7.5g/-2.5g	1 CYCLE +6.5g/-1.5g	2 CYCLES +5g/0g	4 CYCLES +4g/+0.5g	10 CYCLES +3g/+1g

FLIGHT A →	10 CYCLES +3g/+1g	2 CYCLES +4g/+0.5g	2 CYCLES +5g/0g	2 CYCLES +6.5g/-1.5g	2 CYCLES +5g/0g	2 CYCLES +4g/+0.5g	5 CYCLES +3g/+1g

FLIGHT B →	5 CYCLES +3g/+1g	5 CYCLES +4g/+0.5g	9 CYCLES +5g/0g	4 CYCLES +4g/+0.5g	5 CYCLES +3g/+1g

FLIGHT C →	5 CYCLES +3g/+1g	1 CYCLE +4g/+0.5g	5 CYCLES +3g/+1g

CYCLES OF +6.5g/-1.5g AND
+7.5g/-2.5g AT 1 Hz;
REMAINDER OF CYCLES AT 3 Hz

SEQUENCE OF FLIGHTS IN 100 FLIGHTS: 1 FLIGHT A', 18 FLIGHTS A, 36 FLIGHTS B AND 45 FLIGHTS C

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
B	C	C	B	C	C	C	A	C	C	B	B	A	C	C	C	B	A	C	B	B	B	A	C	C
51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
C	B	C	C	B	C	B	B	C	C	C	A	B	A	C	C	C	B	A	B	B	B	C	B	C

26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
C	A	A	C	C	B	B	B	C	B	A	B	C	C	B	A	A'	B	C	C	A	A	B	B	C
76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
C	A	B	C	B	A	B	C	C	B	A	A	B	C	C	B	C	C	B	B	C	B	C	A	C

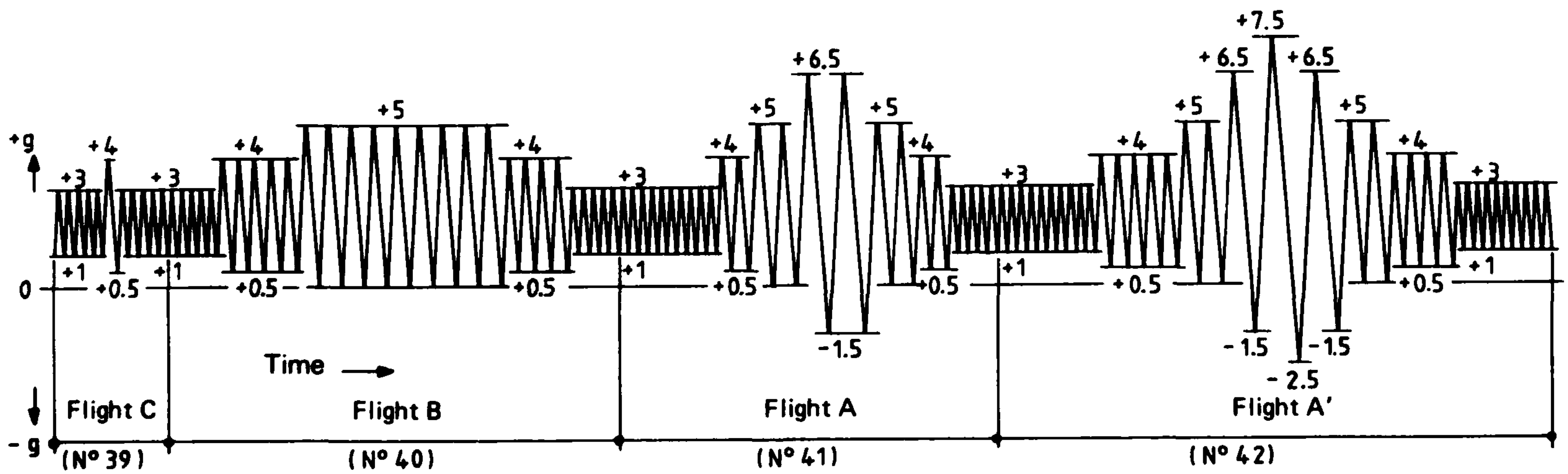


FIG. 5 FRENCH 100 FLIGHT MIRAGE III FLIGHT-BY-FLIGHT SEQUENCE

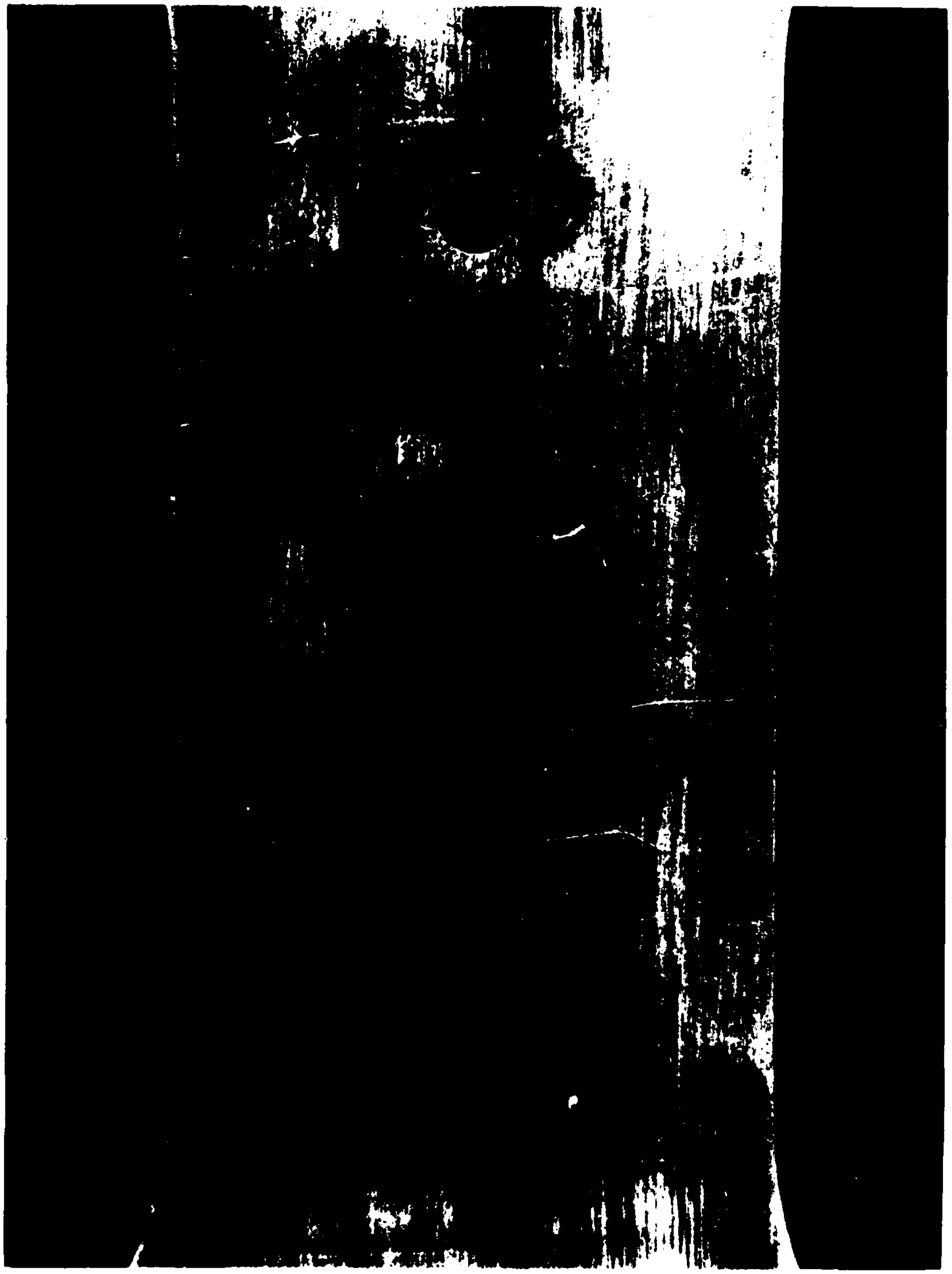


FIG. 6 DEFORMED ZONES ON FACES OF COLD-EXPANDED HOLE SPECIMEN

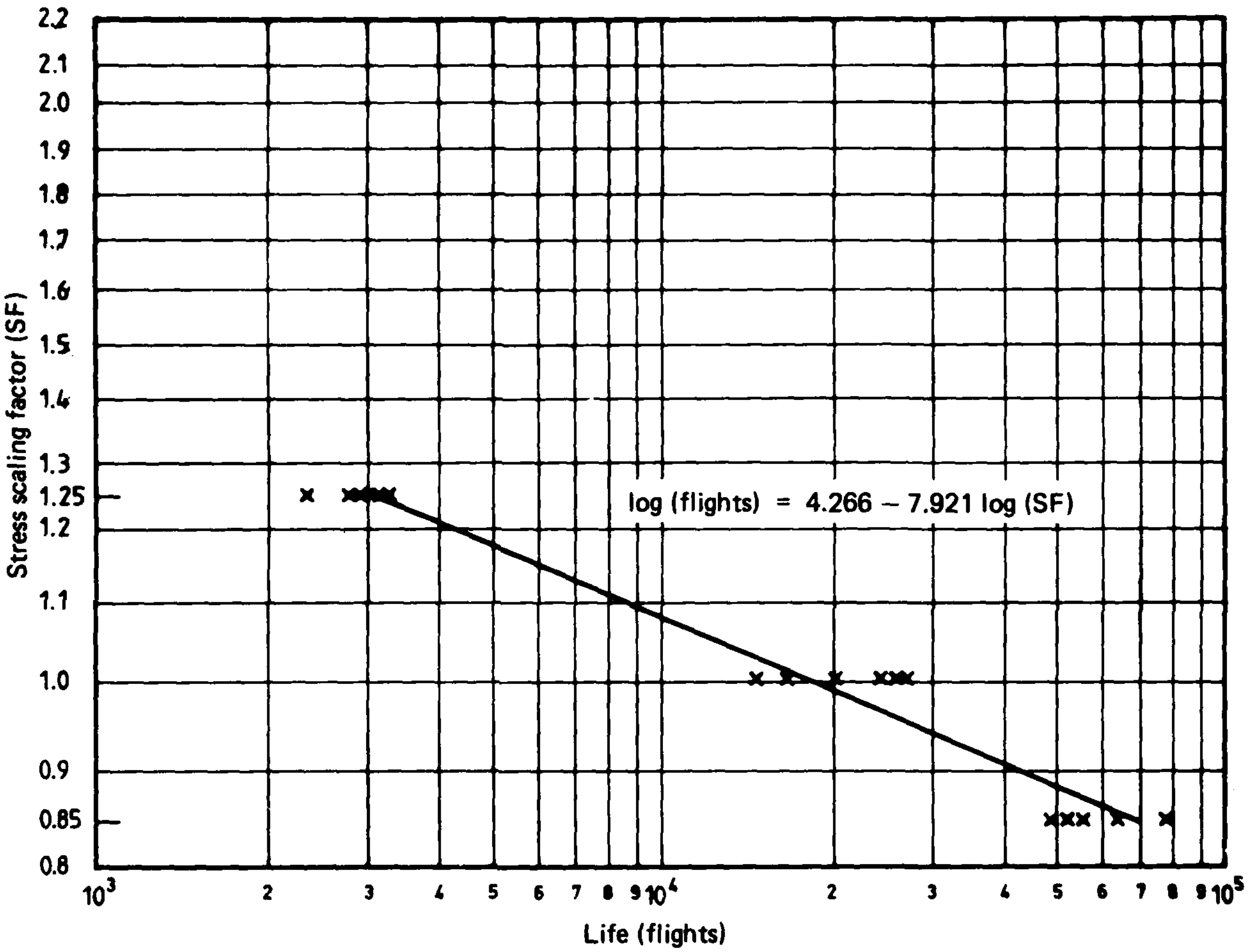
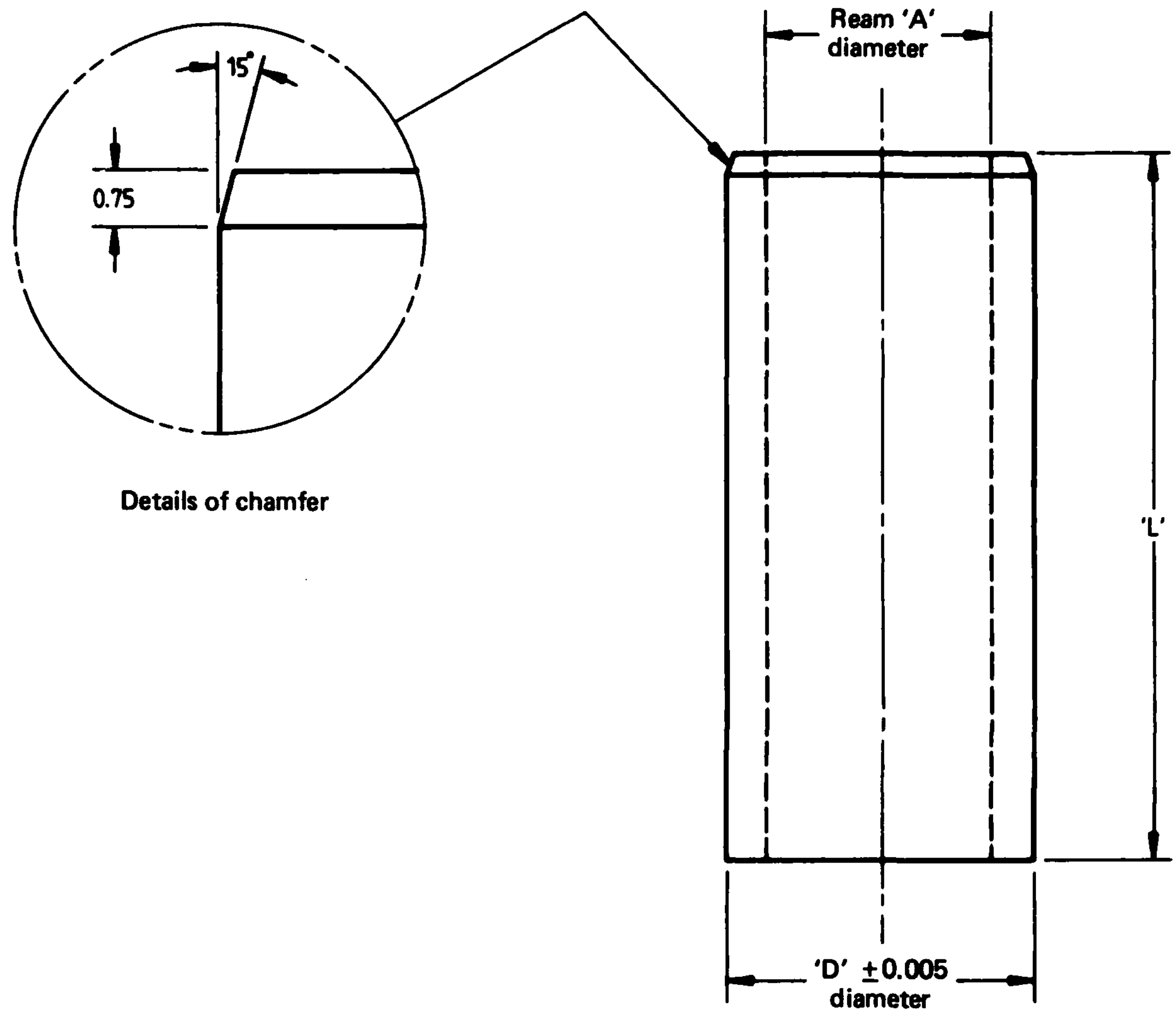


FIG. 7 FATIGUE LIVES OF TYPE (C) COLD-EXPANDED HOLE SPECIMENS AT DIFFERENT STRESS SCALING FACTORS



Nominal hole dia.	'A'	'L'	'D'
7	5.028 5.010	29.5	Hole dia. + 0.3%
8.1	5.028 5.010	29.5	Hole dia. + 0.3%

Notes

1. Diameter 'D' interference 0.25 to 0.35% on hole size
2. Material type 304 stainless steel
3. External surfaces ground finish
4. All dimensions in mm.

FIG. 8 STEEL BUSHES

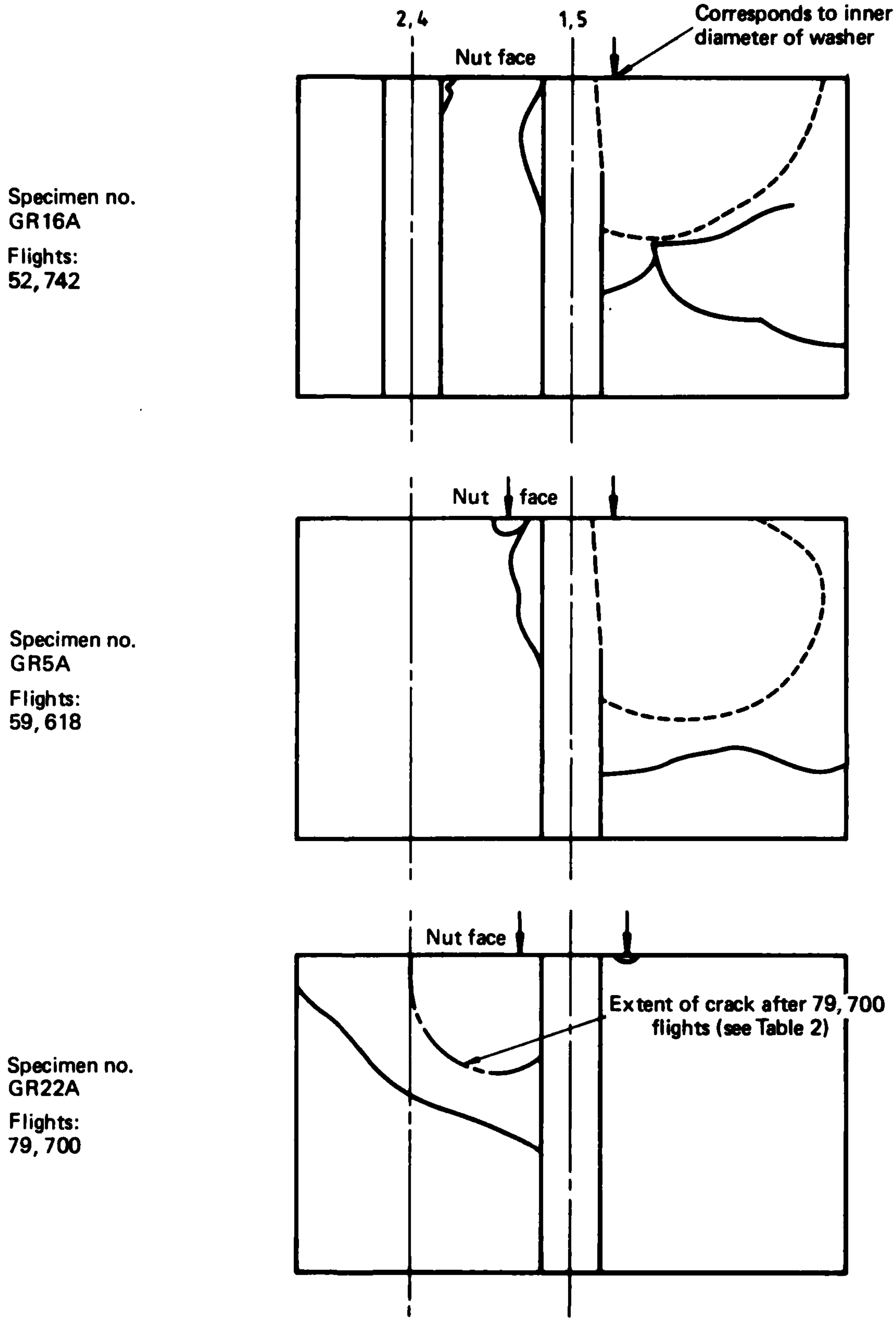


FIG. 9(a) FRACTURE SURFACES: SPECIMEN TYPE (A)
INTERFERENCE – FIT BOLTS

(The full lines indicate the approximate extent of fatigue cracking before final failure, while the dotted lines represent the approximate boundaries of the 'flat' area of the major crack before the development of shear lips at an advanced stage of the crack propagation.)

Specimen no.
GR6B

Flights:
5, 642

Specimen no.
GR3B

Flights:
7, 399

Specimen no.
GR7B

Flights:
8,099
(see also Fig. 10(d))

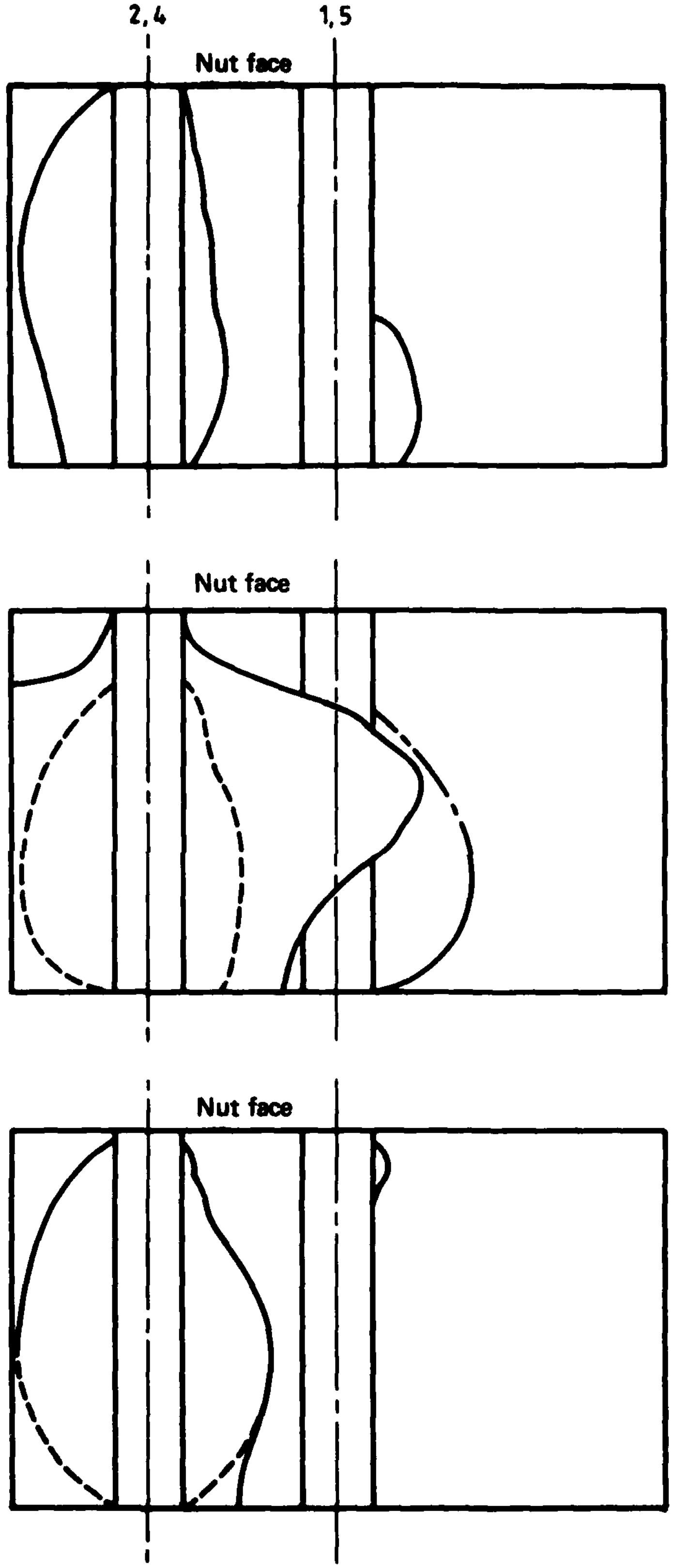


FIG. 9 (b) FRACTURE SURFACES: SPECIMEN TYPE (B)
CLEARANCE – FIT BOLTS

Specimen no.
GR2B
Flights:
8,742

Specimen no.
GR5B
Flights:
9,127
(see also Fig. 11(a))

Specimen no.
GR1B
Flights:
12,942

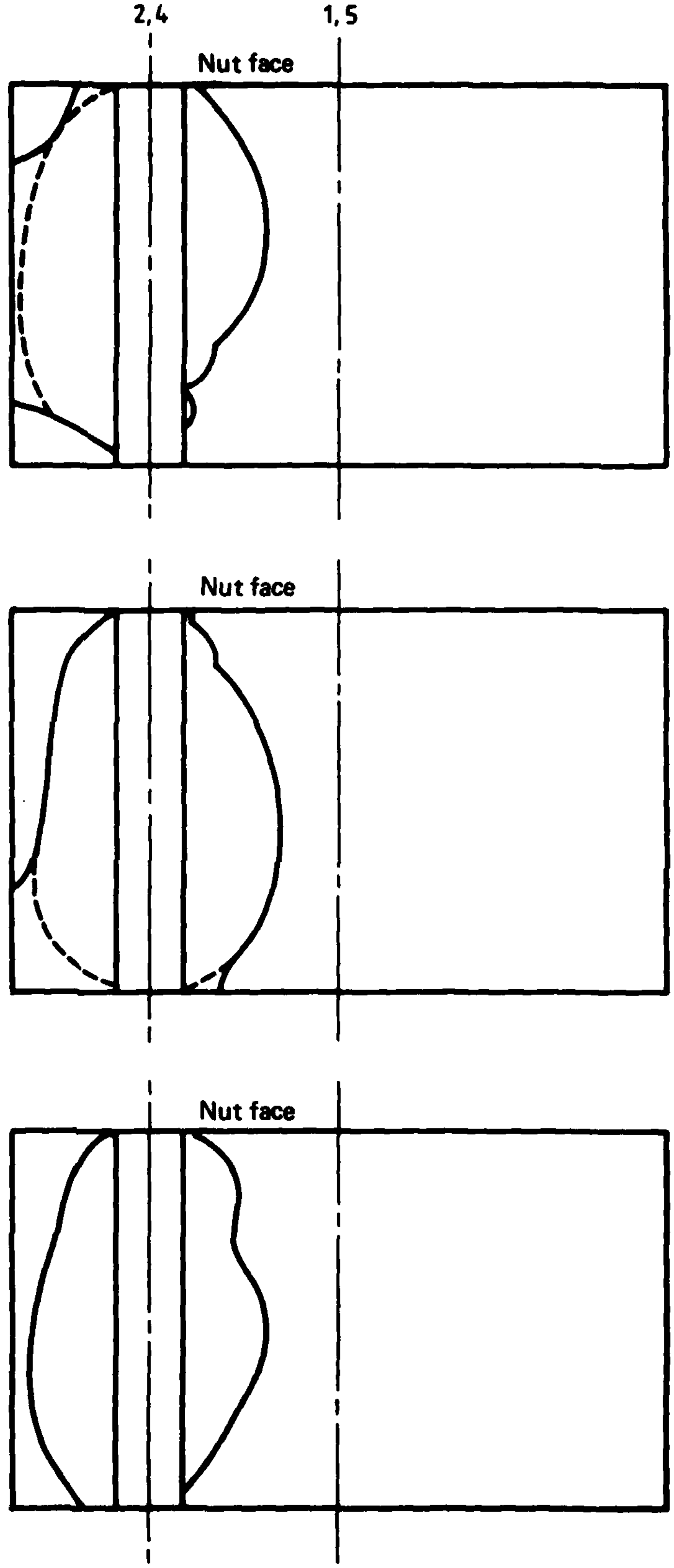


FIG. 9(b) FRACTURE SURFACES: SPECIMEN TYPE (B)
CLEARANCE – FIT BOLTS

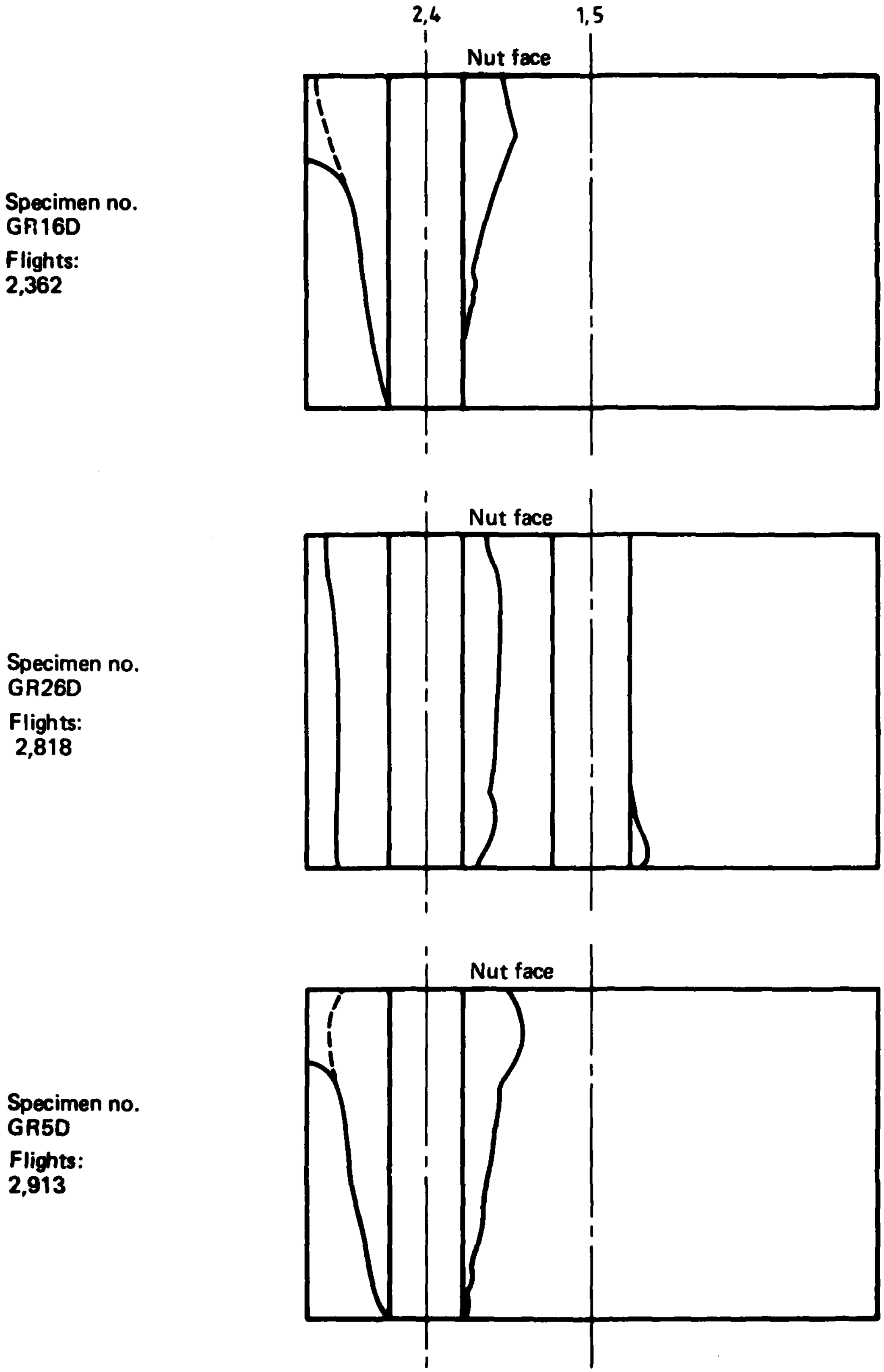


**FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES**

Specimen no.
GR8B

Flights:
3,136

Specimen no.
GR12B

Flights:
3,223

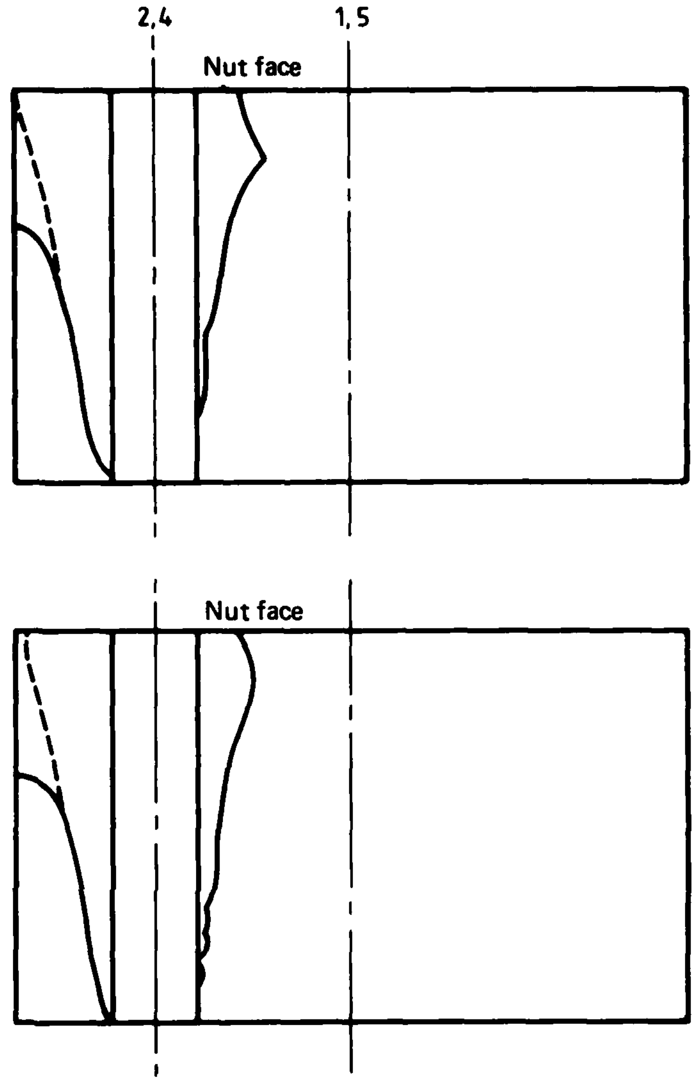


**FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES**

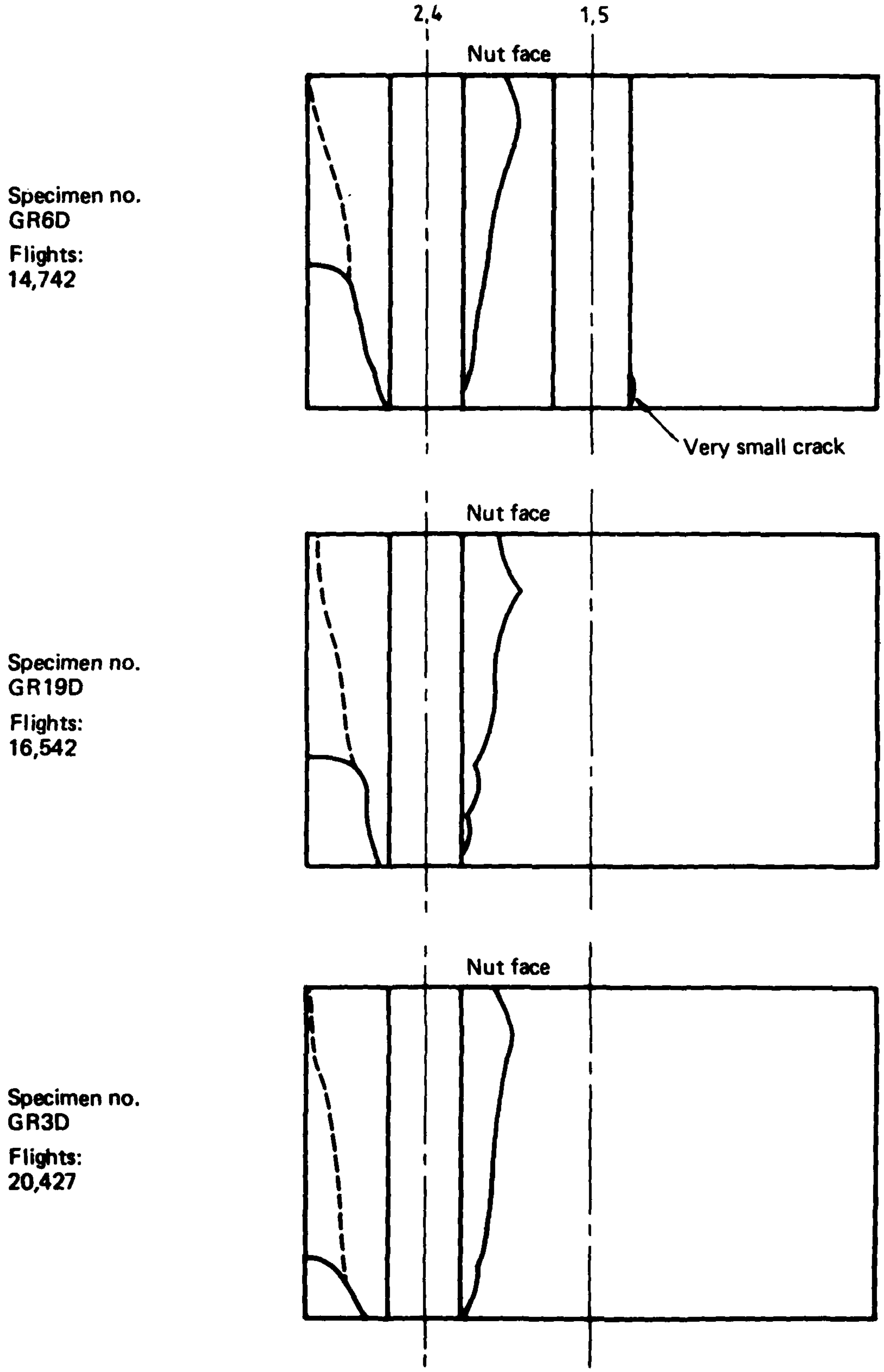


FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES

Specimen no.
GR23D

Flights:
24,413
(see also Fig. 10 (c))

Specimen no.
GR9D

Flights:
25,813
(see also Fig. 11 (b))

Specimen no.
GR11B

Flights:
25,842

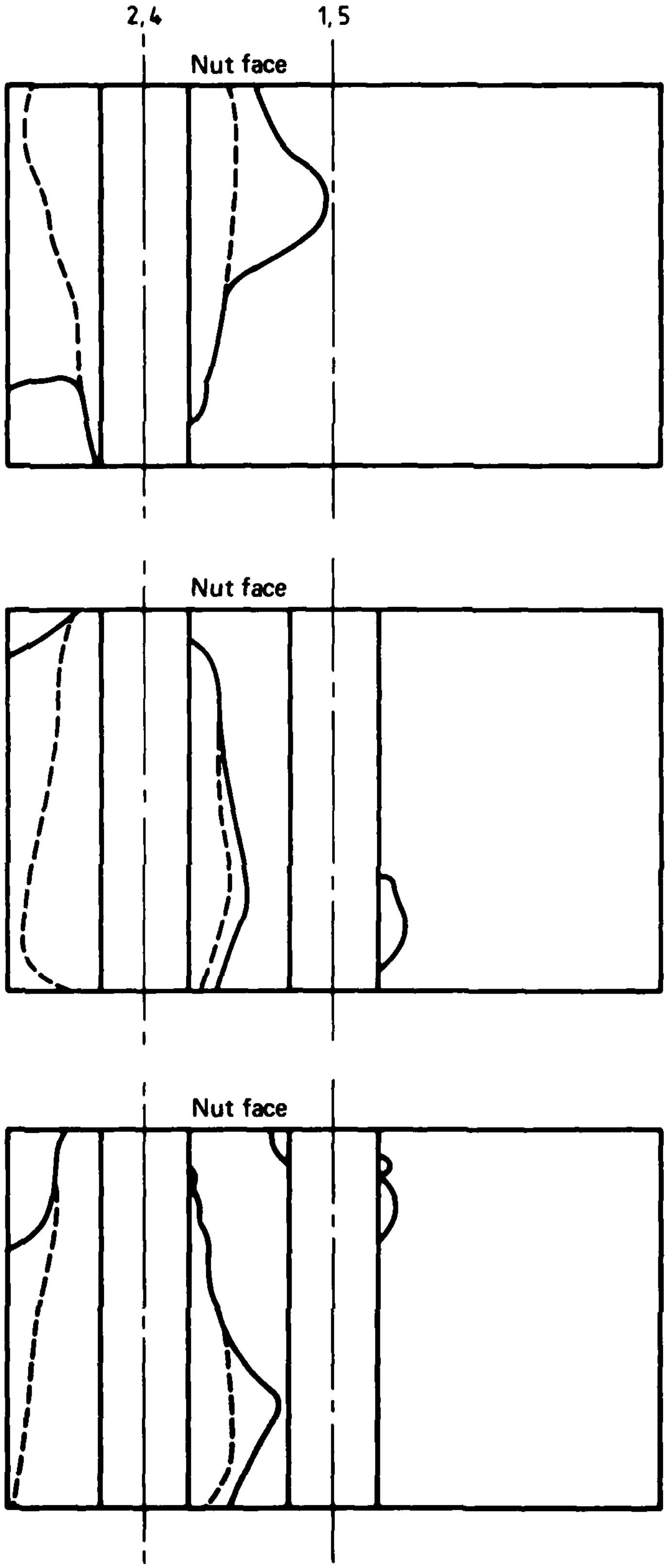
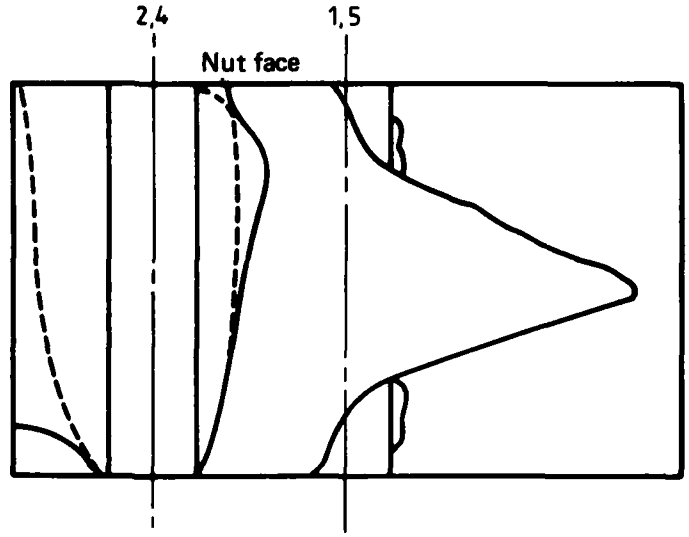


FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C) COLD – EXPANDED HOLES

Specimen no.
GR2D
Flights:
26,781
(see also Fig. 11 (c))



Specimen no.
GR1E
Flights:
24,300
(see also Fig. 10(f))

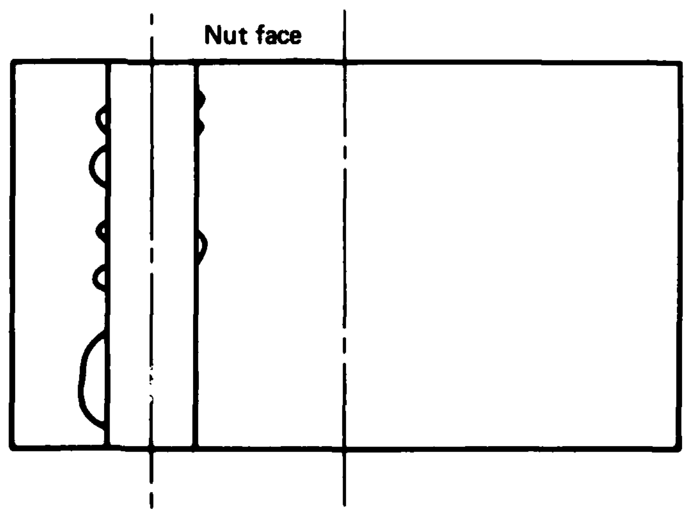
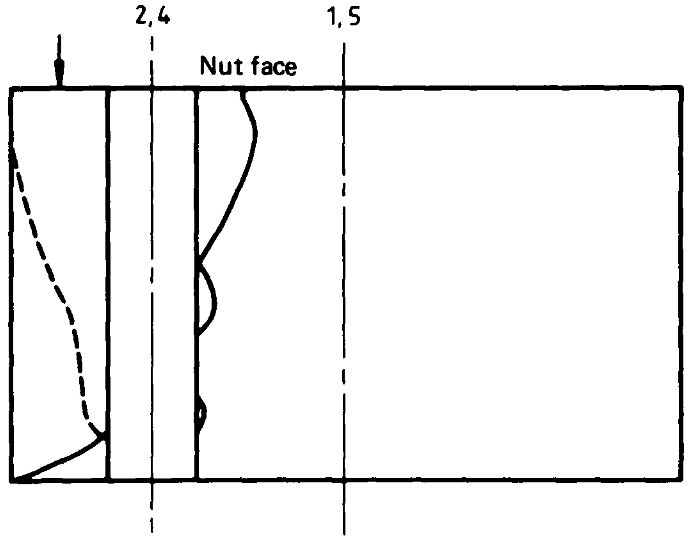


FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES

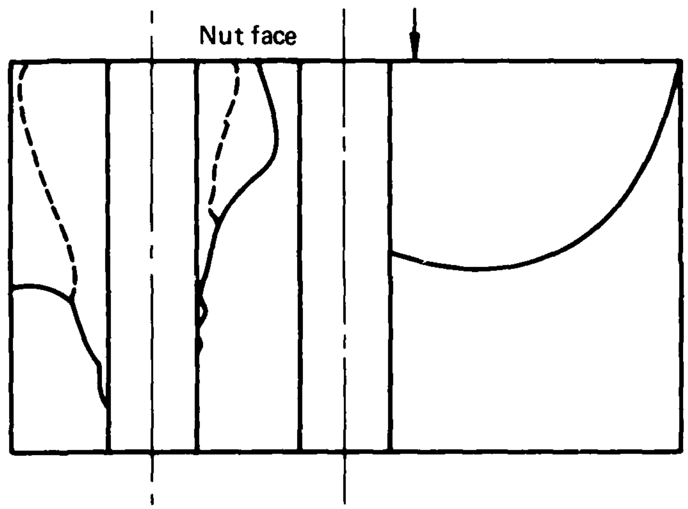
Specimen no.
GR10B

Flights:
49,242



Specimen no.
GR15D

Flights:
51,987



Specimen no.
GR18D

Flights:
55,336

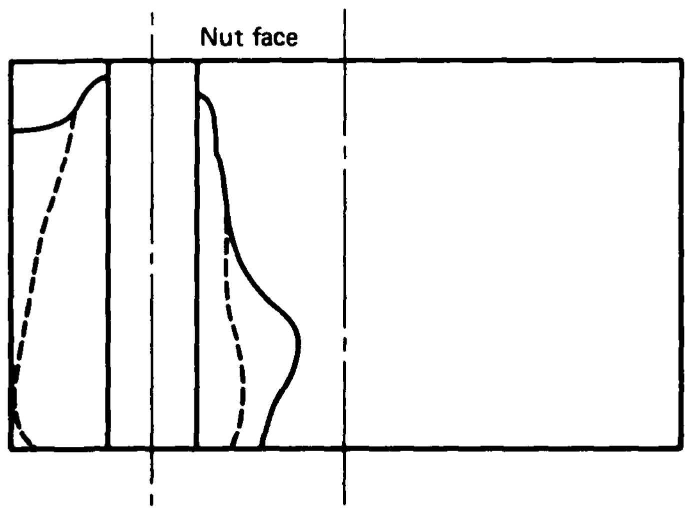


FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES

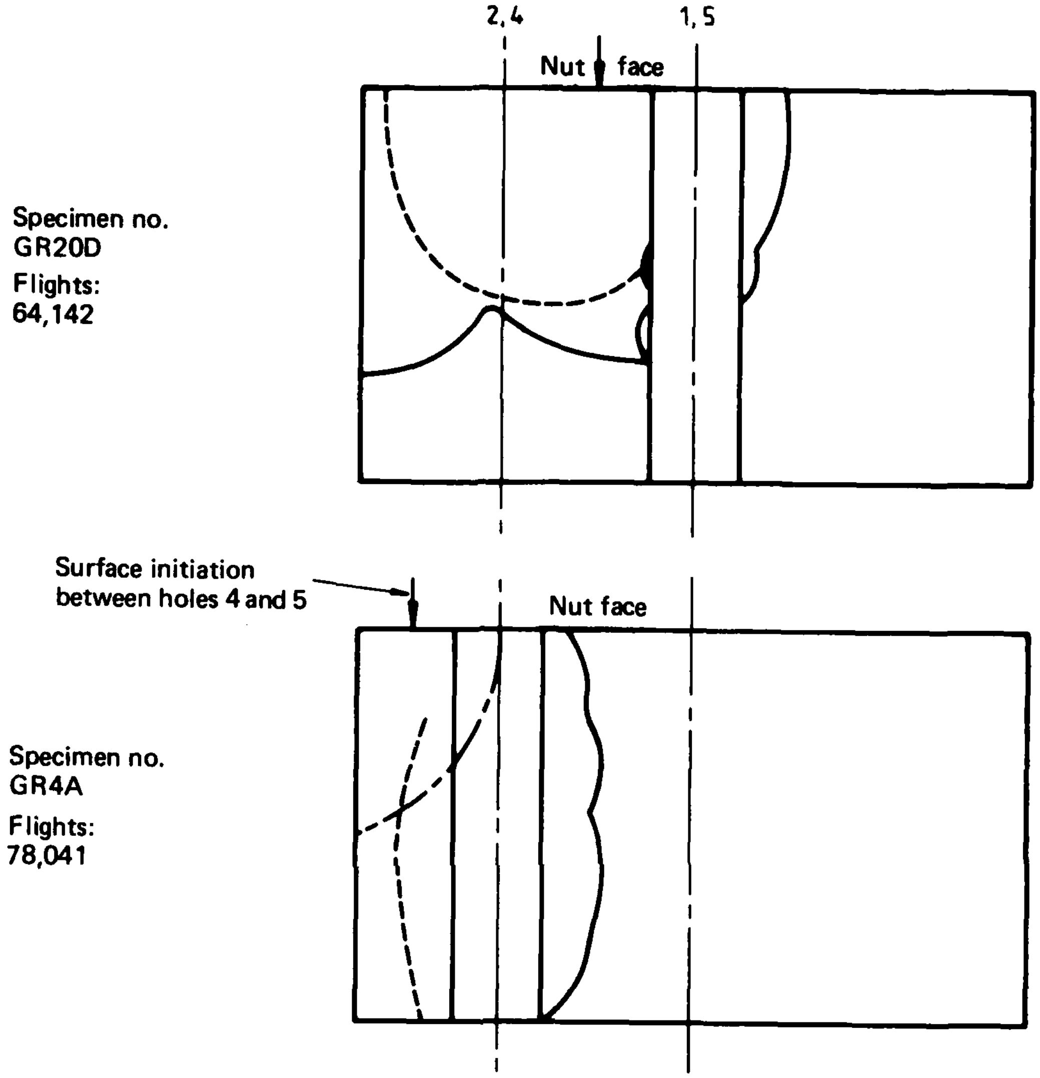


FIG. 9(c) FRACTURE SURFACES: SPECIMEN TYPE (C)
COLD – EXPANDED HOLES

Specimen no.
GR17E
Flights:
27,013

Specimen no.
GR20E
Flights:
30,227
(see also Fig. 10(c))

Specimen no.
GR23E
Flights:
41,242

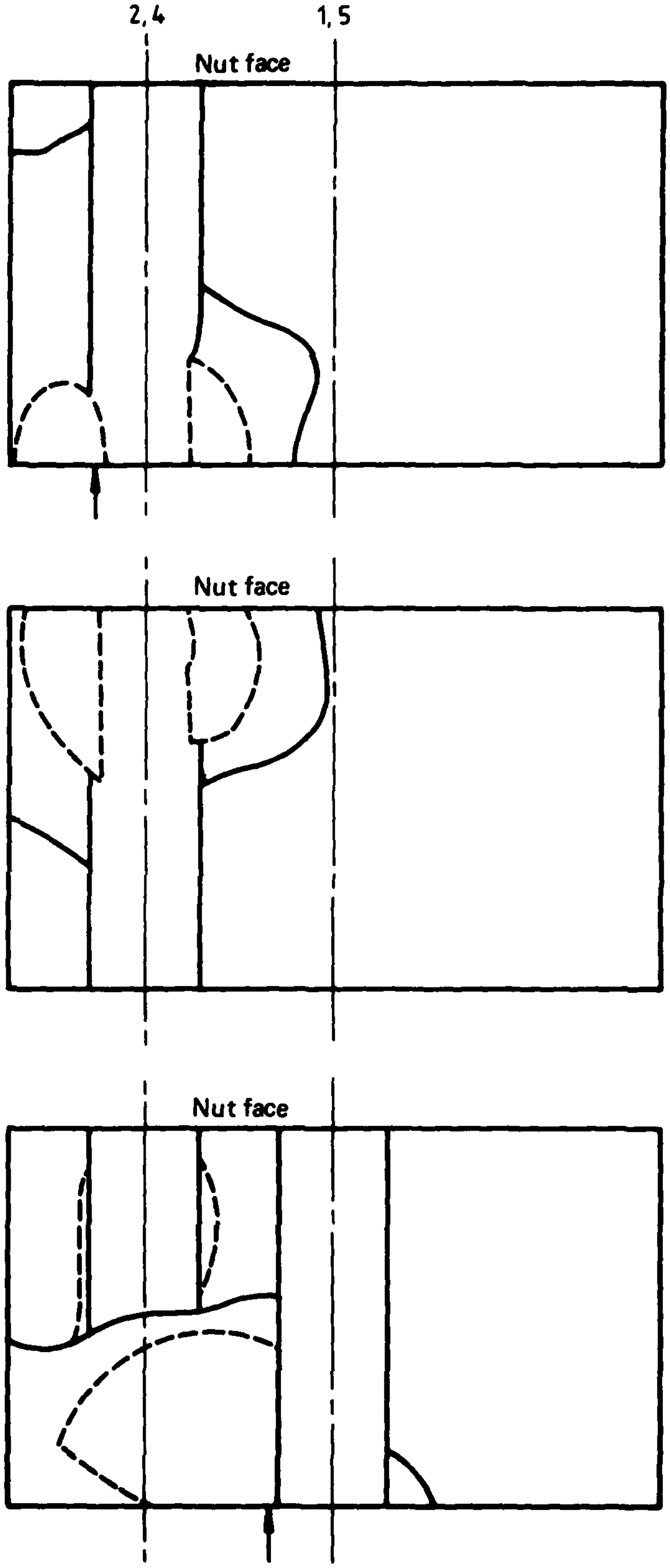
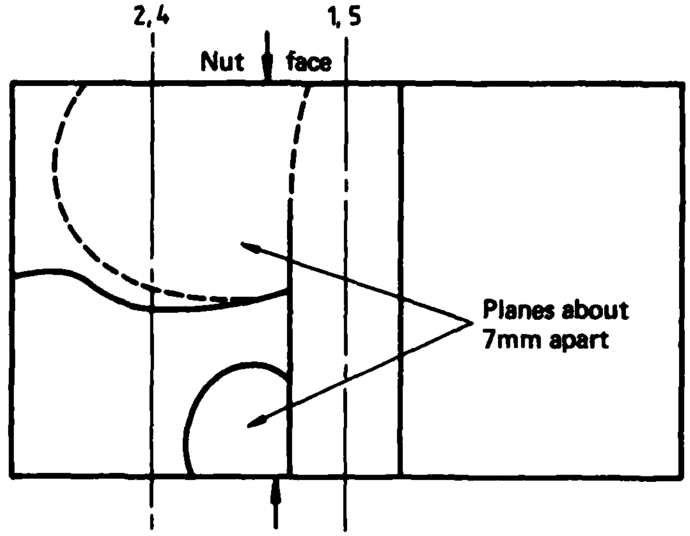


FIG. 9(d) FRACTURE SURFACES: SPECIMEN TYPE (D)
INTERFERENCE – FIT BUSHES

Specimen no.
GR12E

Flights:
41,542



Specimen no.
GR25E

Flights:
61,342
(see also Fig. 10(b))

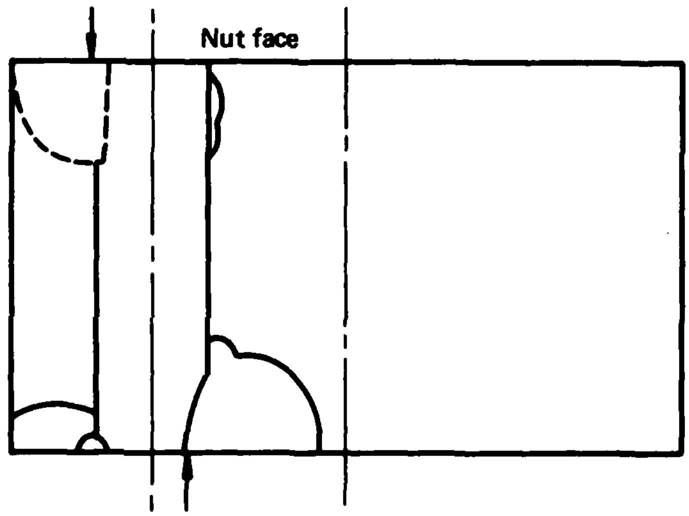
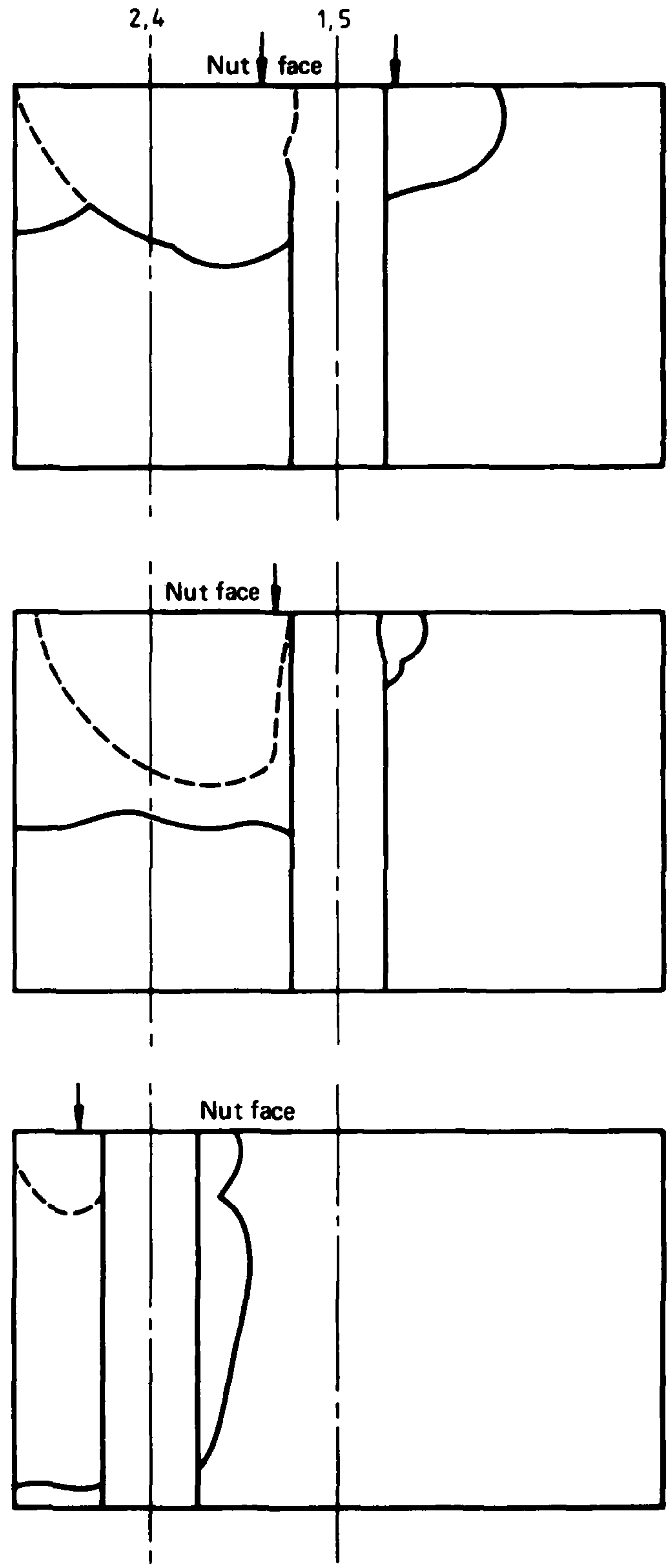


FIG. 9(d) FRACTURE SURFACES: SPECIMEN TYPE (D)
INTERFERENCE – FIT BUSHES



Specimen no.
GR21D
Flights:
48,042

Specimen no.
GR7D
Flights:
54,042
(see also Fig. 10(a))

Specimen no.
GR22D
Flights:
55,542

FIG. 9(e) FRACTURE SURFACES: SPECIMEN TYPE (E)
INTERFERENCE – FIT BUSHES IN COLD –EXPANDED HOLES

Specimen no.
GR11D
Flights:
63,142

Specimen no.
GR17D
Flights:
65,899

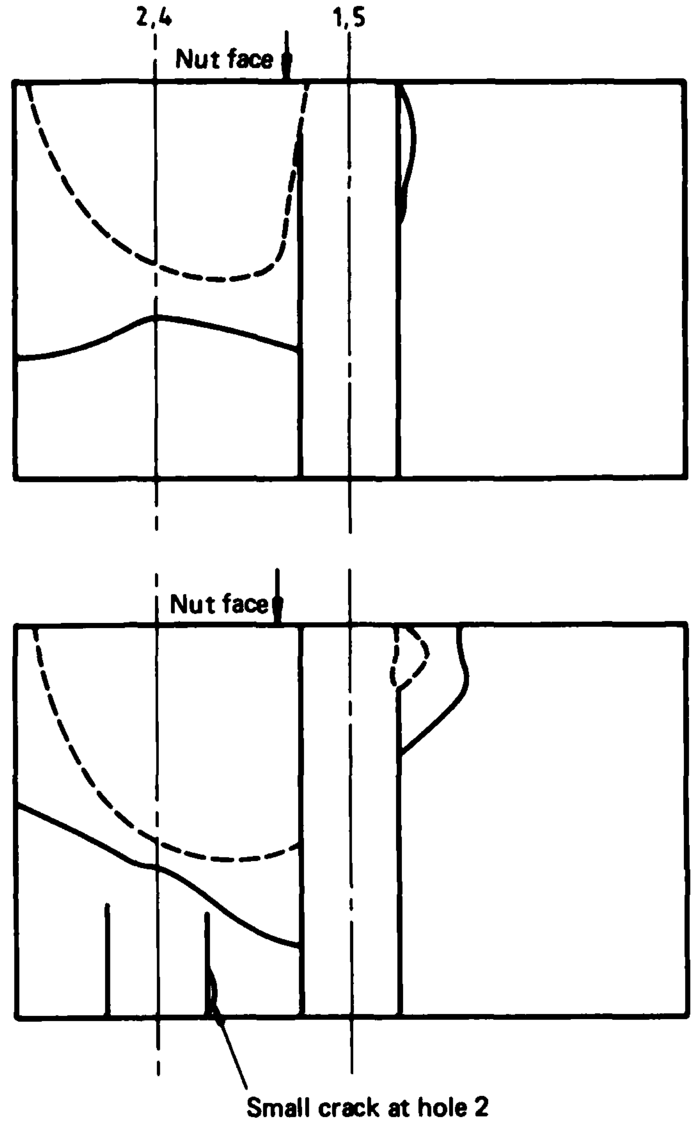
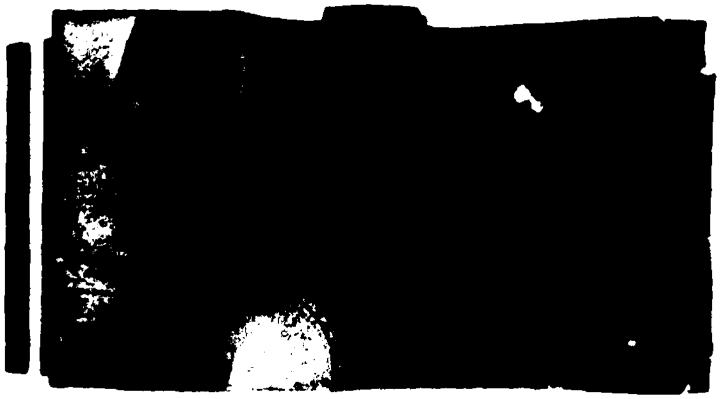


FIG. 9(e) FRACTURE SURFACES: SPECIMEN TYPE (E)
INTERFERENCE FIT – BUSHES IN COLD – EXPANDED HOLES

Nut face

(a) Specimen GR7D – type (E) interference – fit bushes in cold-expanded holes

Nut face



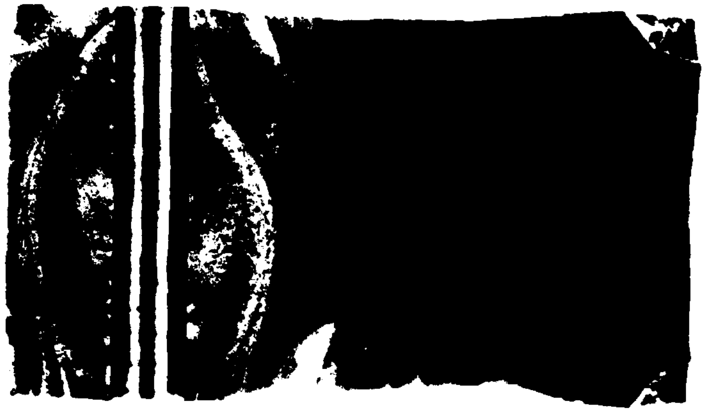
(b) Specimen GR25E – type (D) interference – fit bushes

Nut face

(c) Specimen GR20E – type (D) interference – fit bushes

FIG. 10 REPRESENTATIVE FATIGUE FRACTURES

Nut face



(d) Specimen GR7B – type (B) clearance – fit bolts

Nut face

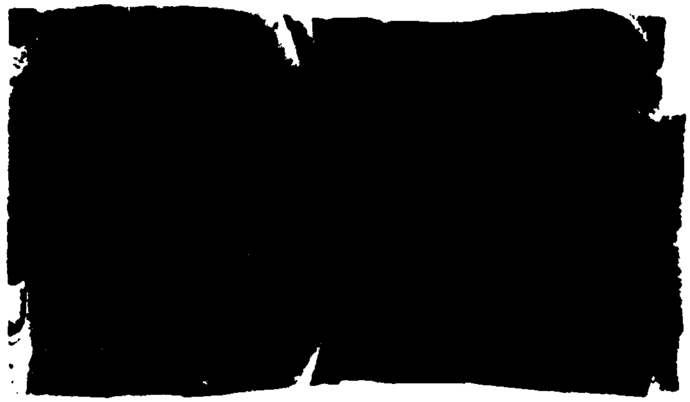
(e) Specimen GR23D –type (C) cold – expanded holes

Nut face

(f) Specimen GR1E –type (C) cold – expanded holes (residual static strength test)

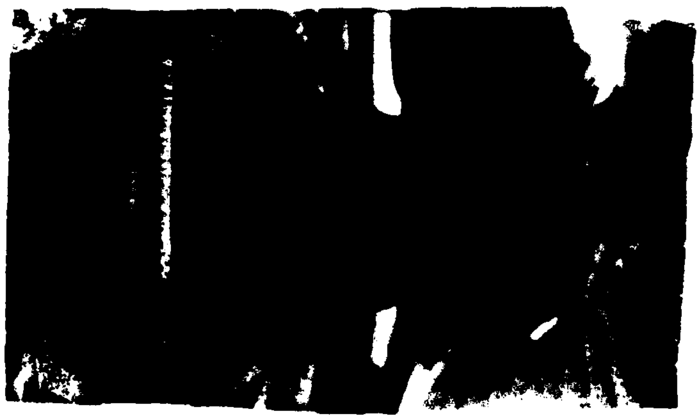
FIG. 10 REPRESENTATIVE FATIGUE FRACTURES

Nut face



(a) Specimen GR5B – type (B) clearance – fit bolts

Nut face



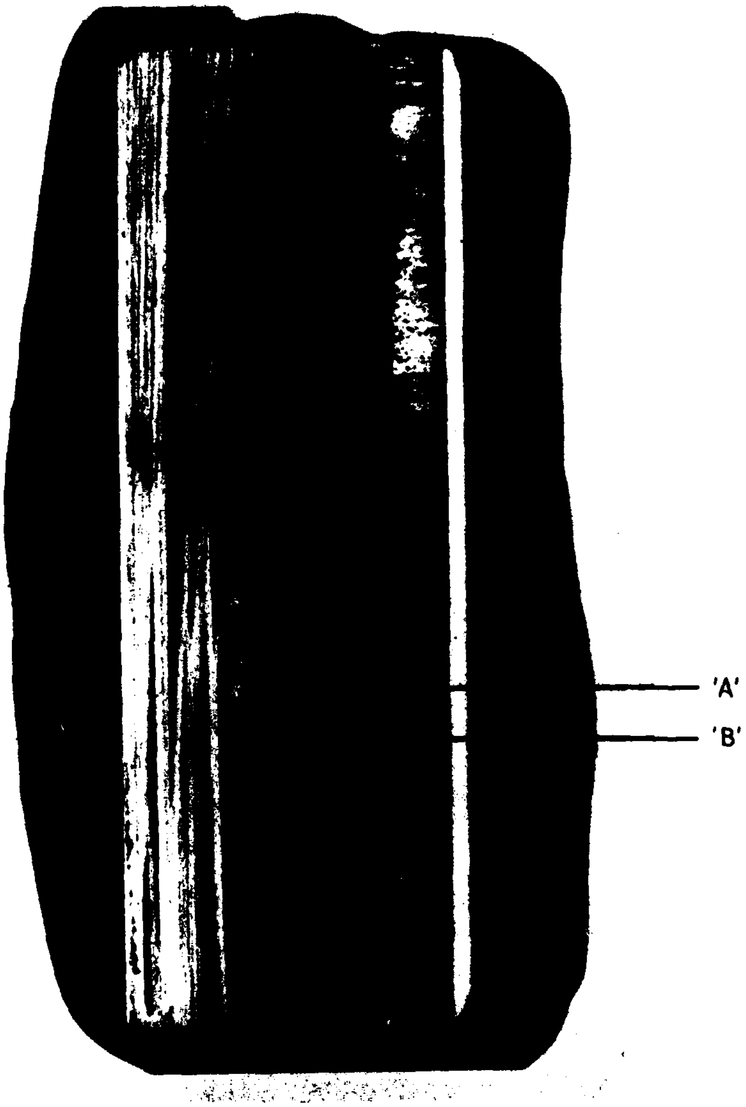
(b) Specimen GR9D –type (C) cold – expanded holes

Nut face

(c) Specimen GR2D – type (C) cold – expanded holes

FIG. 11 SPECIMENS SELECTED FOR CRACK GROWTH MEASUREMENTS

Nut face



(d) Specimen GR3B — type (B) clearance-fit bolts, non-failure hole 2

FIG. 11 SPECIMENS SELECTED FOR CRACK GROWTH MEASUREMENTS

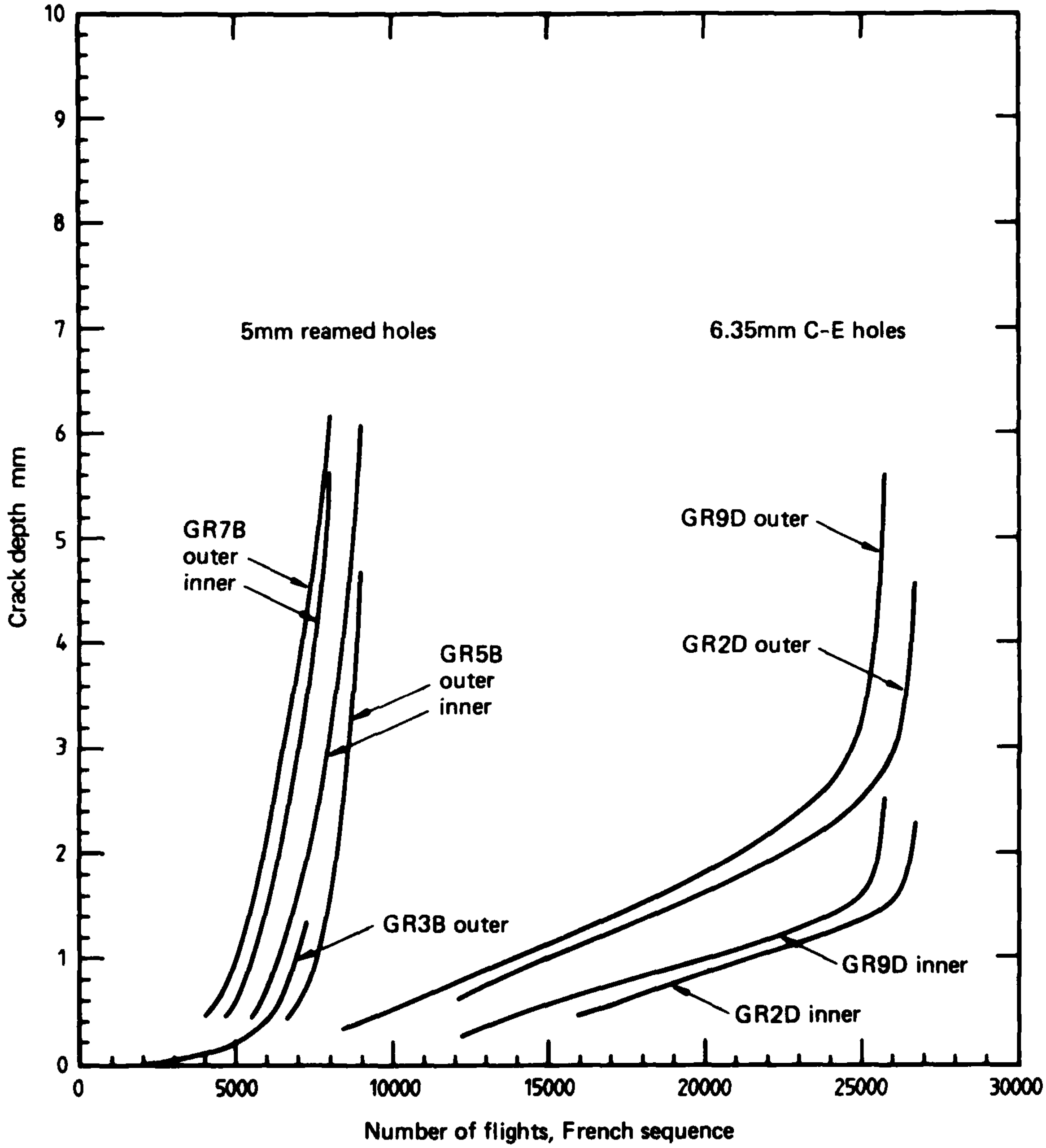


FIG. 12 CRACK GROWTH CURVES FOR REAMED HOLES AND COLD-EXPANDED HOLES FROM FRACTOGRAPHIC MEASUREMENTS

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Bolted joints	Interference fitting	1103
Holes (openings)	Bushings	
Cold working	Aluminium alloys	
Aircraft structures		

16. Abstract

The detection of fatigue cracks at bolt holes in the main spar of the Mirage III wing during full-scale fatigue tests led to a requirement for refurbishment procedures to extend the fatigue lives at a number of critical locations. One of these, which is covered by this investigation, was the spar lower front flange. Flight-by-flight fatigue tests have been carried out to determine the relative fatigue performance of aluminium alloy bolted joint specimens of 28 mm thickness incorporating close-fit bolts, interference-fit bolts (0·4%), hole cold-expansion (3%), interference-fit steel bushes (0·3%) and a combination of cold-expansion and interference-fit bushes.

Compared with joints assembled with close-fit bolts in reamed holes, the ratios of the lives of specimens incorporating interference-fit bolts, interference-fit bushes and cold-expanded bolt holes were about 9:1, 5:1 and 3:1 respectively. Furthermore, specimens with holes cold-expanded followed by the installation of interference-fit bushes resulted in a greater fatigue life than with interference-fit bushes alone.

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16. Abstract (*Contd*)

Fractographic measurements of crack development from the bores of holes in specimens incorporating close-fit bolts in non cold-expanded (reamed) and cold-expanded holes clearly indicated much slower fatigue crack propagation rates from the cold-expanded holes until the crack length was close to the nominal region of transition from the residual compressive to tensile stress zone around the cold-expanded holes.

Fatigue tests on cold-expanded hole specimens at different spectrum scaling factors indicated that, under the loading sequence used, each 10% increase in stress reduced the life to about half that at the lower stress level.

It was concluded that if the refurbishment requirement involved the enlargement of bolt holes to remove fatigue cracks and also the subsequent periodic non-destructive inspection of the holes in service (which would be difficult if interference-fit bolts were used), then the use of interference-fit bushes either alone or in a combination with hole cold-expansion should enable a satisfactory extension in fatigue life to be achieved for the detail of interest in the structure.

17. Imprint

Aeronautical Research Laboratories, Melbourne

18. Document Series and Number	19. Cost Code	20. Type of Report and Period Covered
Structures Note 490	251020	—

21. Computer Programs Used

—

22. Establishment File Ref(s)

—